Direct Search Experiment for Light Dark Matter with Superfluid Helium

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Research area: Direct Dark Matter detection at sub-GeV masses with calorimetric detectors.

Overall Description of the Research Unit and the Coordination Proposal

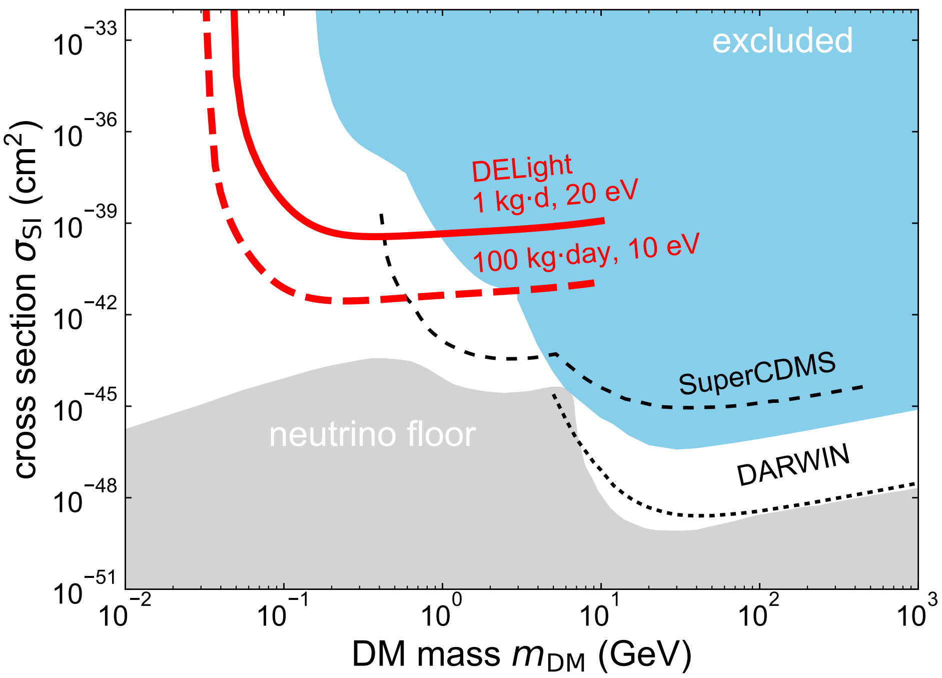

Figure 1: Projected spin-independent (SI) dark matter-nucleon scattering limits at 90% confidence level assuming zero background and the minimum DELight goals in terms of exposure and threshold for phase-I (red solid line) and phase-II (red dashed line) [1]. Also shown are the neutrino signal region in helium (gray area) calculated as described in Ref. [2], already excluded parameter space [3–6] (blue area) and the projected limits by DARWIN [7] and SuperCDMS [8] (black dashed lines).

Contents

1 State of the art and preliminary work

The particle nature of Dark Matter (DM) is one of the leading questions in modern physics and is in the focus of world-wide research. A core class of experiments searching for DM particles are direct detection experiments with the goal to directly observe ultra-rare interactions of DM with the target material of the detector. Common target materials include xenon, argon, germanium, and silicon [9].

Within this Research Unit (RU) the new "Direct search Experiment for Light dark matter", DELight, is proposed [1], combining the complementary expertise of leading scientists at Heidelberg University (UHD), the University of Freiburg (UFR), and the Karlsruhe Institute of Technology (KIT). DELight is being designed to reach world-leading sensitivity at masses well below the GeV-scale in DM-nucleus scattering interactions. To reach ultra-low detection thresholds necessary to probe unprecedentedly low DM masses, target material alternatives and novel detector designs are essential. One such target material is superfluid ^{4}He as will be used by DELight, instrumented with Magnetic MicroCalorimeters (MMCs) [10]. **Already with a small exposure of 1 kg·d and a moderate threshold of about 20 eV, as planned during phase-I of DELight, a DM-nucleon scattering cross section of $< 10^{-39}$ cm^2 at 200 MeV can be probed, improving on current constraints by three orders of magnitude, and masses of weakly interacting DM candidates notably below 100 MeV become accessible for the first time.** It should be noted that the few existing limits reaching down to about 50 MeV are at cross sections well above 10^{-32} cm^2 [11]. At cross sections above about 10^{-33} cm^2 the interaction rate is so high, though, that earth and atmosphere shielding must be taken into account. Once shielding is included, most of the parameter space below 100 MeV is not accessible anymore in these cases as demonstrated in Ref. [11].

In addition to these crucial results achievable during the funding period of the RU, a basis will be established for the long-range plan of DELight which targets an exposure of ≥ 1 kg·yr acquired with a He volume of up to 200 ℓ in an underground laboratory. This size of the experiment will be reached in a staged approach, increasing the target volume and number of sensors in at least two stages together with potential further improvements on the design and choice of materials. For phase-II an exposure of 100 kg·d and a threshold of 10 eV is anticipated. In a next stage, with an exposure of at least 1 kg·yr and an anticipated energy threshold of $\lesssim$ 10 eV, a DM mass of $\lesssim$ 30 MeV becomes accessible and the overall sensitivity on the scattering cross section approaches the unavoidable neutrino background, also referred to as neutrino floor.

State of the art

The Standard Model (SM) of particle physics is a self-consistent theory, which has successfully predicted experimental findings to huge accuracy. However, the SM is incomplete, failing to explain a multitude of astrophysical and cosmological observations [12–14]. These observations strongly suggest the existence of a new type of matter that cannot be directly observed with telescopes, so-called Dark Matter. The existence of DM is supported by a plethora of further observations [15–17] including patterns of anisotropies in the Cosmic Microwave Background (CMB) radiation temperature [18]. It is a well-established concept in particle physics, astrophysics and cosmology, and a key component in the Lambda Cold Dark Matter (ΛCDM) model of Big Bang cosmology. A fit of the ΛCDM model to the power spectrum of the CMB anisotropies predicts that DM constitutes about 85% of all matter in the Universe [18]. **Still, although there is compelling evidence for DM, its nature is unknown and DM particles have yet to be discovered, an endeavor the proposed RU is dedicated to contribute to.**

There are few clearly established properties of particle DM: its relic density in the Universe, a particle lifetime significantly longer than the age of the Universe, and couplings to SM particles at the weak scale or below. The ΛCDM model further requires DM to be non-baryonic and non-relativistic, a property necessary to explain the observed structure formation in the Universe. This leads to the conclusion that DM is composed of new particles beyond the SM. A great variety of theoretical DM particle candidates exists spanning many orders of magnitude in mass and coupling strength [19]. Ongoing and planned experiments are only sensitive to a subset of these candidates including the so-called Weakly-Interacting Massive Particles (WIMPs), which have mass and coupling(s) around the weak scale and are produced from thermal equilibrium in the early Universe. Ongoing experimental efforts to detect WIMPs include direct detection experiments, designed to measure their scattering off nuclei in the laboratory, indirect detection experiments, searching for secondary particles from WIMP decays, as well as attempts to produce them in colliders like the LHC. Those searches have not yet discovered WIMPs but have excluded their most simple models with DM masses close to the weak scale [19]. A possible explanation is that the DM particle is lighter than predicted by the standard WIMP paradigm and has a mass below the GeV scale, a possibility that is currently the subject of much theoretical and experimental interest [20]. Such WIMP-like sub-GeV DM particles are commonly referred to as Light DM (LDM) and their potential couplings have been barely probed thus far. **The DELight experiment will be built to thoroughly explore the LDM region in DM-nucleus scattering searches down to unprecedentedly low masses of a few tens of MeV.**

Sensitivity to LDM in DM-nucleus scattering interactions requires light target elements and very low detection thresholds. The observable nuclear recoil energy decreases with decreasing DM particle mass and with increasing mass of the recoiling nucleus. Helium is very light compared to typical direct detection target elements like Xe, Ar, Ge and Si. Consequently, the energy transfer from the LDM particle to a target nucleus in a scattering event is more efficient and the resulting signals reach higher amplitudes naturally providing sensitivity to lower DM masses.

DELight uses a well-established detection concept, based on the properties of the superfluid phase of the noble gas ^{4}He, and combines it with state-of-the-art MMC technology, which is now at a point that enables a highly competitive LDM direct detection experiment. Besides its low nuclear mass and the fact that helium is inexpensive, superfluid He has many attractive features making it an excellent choice as target material for LDM searches. It has no intrinsic long-lived radioisotopes, its first excited nuclear state is around 21 MeV [21], it has a high impedance to external vibration noise, and it is self-cleaning in that all other atomic species freeze out, making it a radiopure target. When a particle interacts in the superfluid the initial energy deposition initiates a cascade of processes eventually terminating with the energy distributed among quasiparticles (phonons and

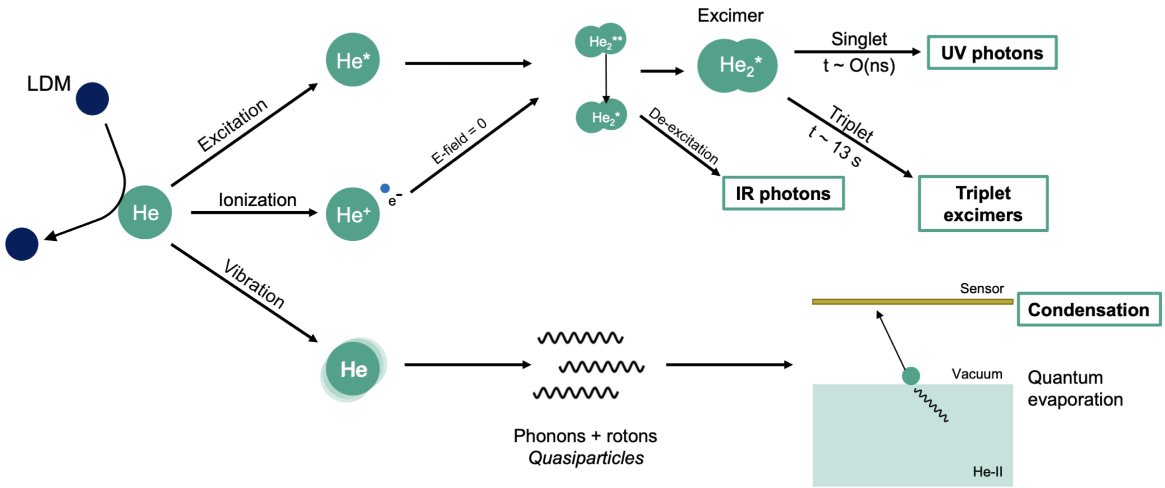

Figure 2: Decay scheme and principal detection channels following a recoil event in superfluid helium.

rotons), photons and a few long-lived excimers as shown in Fig. 2. How the energy is divided among these channels depends on the primary ionization density, providing the means for event classification and background suppression [22]. Quasiparticles radiated from the interaction site propagate ballistically at typical speeds of 150-200 m/s. Those which reach the free surface of the liquid with an energy greater than the binding energy of He to itself can cause quantum evaporation, a process in which one quasiparticle extracts one He atom from the bulk [23]. Particularly for rotons, energy and momentum conservation at the evaporation surface constrain the range of incident angles able to cause evaporation [24, 25]. The He binding energy is 0.62 meV and the typical quasiparticle energies involved are ≥ 0.8 meV. Thus for a nuclear recoil above the anticipated DELight threshold of a few tens of eV, a large population of atoms constitutes the resulting evaporation burst. In addition to quasiparticles, He_2^* excimers are produced in each event providing two additional detection channels: excimers in the singlet state decay within few ns emitting UV photons with a peak energy of 16 eV, while triplet excimers are metastable and observable as ballistic molecules [26]. Since the first excited state of atomic He is at ~ 20 eV, the liquid is transparent to these UV photons.

The basic principles of a particle detector based on superfluid He were already developed in the 1990s and proven in the HERON project [27–30]. HERON was built to measure solar neutrinos with a 3 ℓ superfluid ^{4}He detector operated at 30 mK. Using movable radioactive sources the basic detection scheme was established: the generation of ballistic, athermal quasiparticles traveling to the liquid surface causing quantum evaporation. The evaporated He atoms subsequently condensed on a thin Si wafer, bare of superfluid He, positioned directly above the liquid. The binding energy of He to Si is about ten times stronger than to He in the superfluid phase, providing a signal amplification of roughly a factor of ten. To avoid the superfluid He to cover the Si surface due to its capillarity force overcoming gravity [31], a baffled film burner device was developed [32]. The principle of this voltage-free (and thus noise-free) gain has recently been confirmed by the HeRALD collaboration, using a Transition-Edge Sensor (TES) based calorimeter with a Si substrate to observe, among others, the quasiparticle signal generated in a superfluid ^{4}He target [33]. In contrast to HERON and DELight, HeRALD investigates the usage of an unoxidized Cs film for film-blocking.

The idea of using a superfluid He detector for DM searches, first proposed by the HERON collaboration, dates back to 1988 [34, 35]. At the time LDM was not favored and this idea was

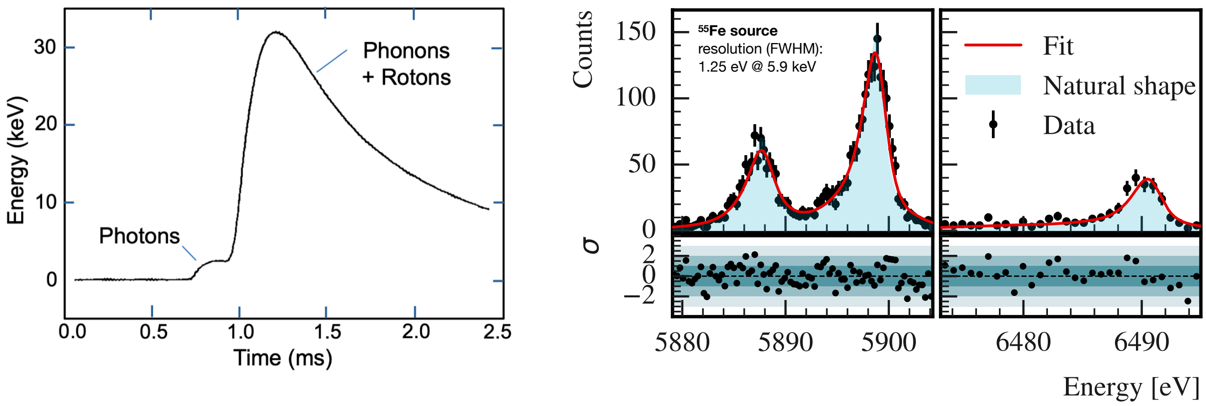

Figure 3: (left) Measured averaged prompt photon and delayed phonon + roton signal induced by 3.3 MeV α-particles in superfluid He [29]. (right) Energy spectra measured with an X-ray detector based on magnetic microcalorimeter technology with SQUID readout [47, 48].

only revisited many years later [36, 37], strongly supported by theoretical and phenomenological studies [19, 38, 39]. Meanwhile careful Monte Carlo simulations have been carried out to simulate possible backgrounds and sensitivities underscoring the vast opportunities of such a detector [40]. It was further demonstrated that the singlet and triplet excimer signals can be separated and that single 15 eV photons can be detected within superfluid He [26]. Also possible advanced detection schemes involving field ionization have been proposed to enhance the sensitivity of superfluid He DM detectors [41]. Recently, it has been pointed out that a DM detector based on superfluid He can potentially use directional information for the identification of DM-nucleus scattering events with recoil energies down to a few keV [42]. **DELight aims to demonstrate that using directional information, the otherwise limiting neutrino floor can in principle be exceeded [29, 43, 44].**

For phase-I of DELight a detector module with a 10 ℓ superfluid He target will be developed and instrumented with the well-established MMCs. MMCs are state-of-the-art cryogenic radiation and particle detectors developed by the low temperature groups at UHD and KIT [10, 45, 46]. They consist of an absorber suitable for the particles of interest, which is in good thermal contact with a paramagnetic temperature sensor. Together they are weakly linked to a thermal bath. The sensor is placed in a weak magnetic field to create a temperature dependent magnetization. A change of temperature, and thus magnetization, resulting from a particle-induced energy deposition, can be precisely measured with a Superconducting QUantum Interference Device (SQUID). Today's MMCs are based on a planar geometry, fully compatible with micro-fabrication processes, and have reached unmatched resolving powers $E/\Delta E_{\mathrm{FWHM}}$ of up to about 5000 [47]. Within DELight, MMCs will be used for both particle detection above the liquid, targeting evaporated He atoms and UV photons, as well as for particle detection in the liquid, detecting UV photons and long-living triplet excimers.

Building on the local experience, originating in the HERON project, and the combined expertise of the applicants in low-temperature physics, cryogenic detector technology, low-background techniques and rare event searches, a highly competitive LDM detector will be built within this RU.

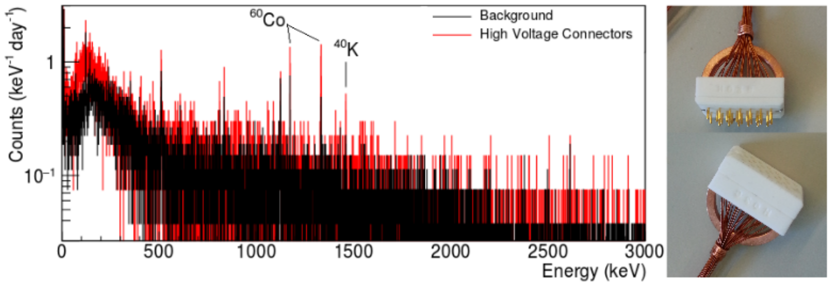

Figure 4: The γ-spectrum of several multi-channel low-background high-voltage connectors (photo), developed for liquid xenon-based DM searches, measured with the GeMSE low-background spectrometer [50].

Preliminary work and project-specific qualifications of participants

Within the proposed RU, researchers with different backgrounds in astroparticle and particle physics as well as condensed matter physics, ultra-low temperatures and quantum sensors join their complementary expertise to realize DELight. A multitude of achievements by the (co-)applicants prior to DELight will serve as important groundwork. C. Enss was part of the group which first proposed the use of superfluid He as DM target [35]. He co-developed the relevant liquid He technologies (see Fig. 3, left) within the HERON project [34, 35], including the realization of a superfluid He cell with film burner [30, 32]. Together with L. Gastaldo and S. Kempf, he drove the technology of cryogenic MMCs [10, 45, 46] which nowadays have ample application in astroparticle physics (e.g., in the neutrino experiment ECHo [49]) and will be used for DELight. A recent version of an MMC-based wafer calorimeter, developed by S. Kempf and his group, reached a world-leading energy resolution in the energy range up to 10 keV among all known comparable energy-dispersive X-ray detectors (see Fig. 3, right) [47, 48].The respective analysis was conducted by DELight collaboration members within the groups of B. v. Krosigk, T. Ferber, and M. Klute, yielding a full width at half maximum of $\left(1.25 \pm 0.17(\text{stat})^{+0.07}_{-0.05}(\text{syst})\right)$ eV at 5.9 keV. Furthermore, S. Kempf (as scientific director) and C. Enss are members of the Center for High-resolution Superconducting Sensors (HSS) at KIT, a unique infrastructure facility currently built up for characterization and large-volume fabrication of cryogenic detectors and superconducting electronics such as MMCs and SQUIDs, that will be available to DELight. Additional expertise on experiments working at ultra-low temperatures comes from B. v. Krosigk and K. Eitel who are experts on cryogenic Si and Ge calorimeters operated at mK-temperatures.

An indispensable aspect of any rare-event search is the reduction of backgrounds, achieved by a combination of detector design, shielding and the careful selection of radiopure components (see Fig. 4). This is a core expertise of M. Schumann, S. Lindemann, K. Valerius, B. v. Krosigk, and K. Eitel who are leading members in the XENON [51], DARWIN [7], SuperCDMS [8] and EDELWEISS [52] experiments. M. Schumann led the overall design and construction of the XENON1T [53] and XENONnT [51] liquid-xenon time projection chambers (TPC), the latter currently being one of the most sensitive detectors for medium to heavy mass DM [54]. S. Lindemann has designed and built the field cage of XENONnT [55]. K. Eitel has ample expertise in building veto detector systems [56]. Preliminary simulation-based studies for DELight have already started to determine the impact of the laboratory overburden on the background rates. DELight will initially be set-up at UHD, but soon after the first data taking, moving to an underground location will be considered to further reduce the background rate. The proposed RU has access to the Swiss Vue-des-Alpes (VdA) underground laboratory [57] via the UFR group. The UFR group further operates facilities for the identification of low-background materials [50], providing crucial infrastructure for DELight, and their γ-spectrometer is installed in a shield similar to the one foreseen for DELight.

B. v. Krosigk and M. Schumann have developed data acquisition (DAQ) and triggering systems for DM detectors [58–60] whose design will serve as base models for the DELight system. T. Ferber and M. Klute are experts for the triggering, data processing and computing systems for Belle II and CMS, respectively, and in developing machine-learning based reconstruction algorithms and software [61]. The powerful computing systems, software frameworks, and reconstruction algorithms set up in this context will guide their development within DELight for their efficient realization.

Many of the proponents have leading roles in data analysis efforts: K. Valerius, B. v. Krosigk, and M. Schumann have all served in the analysis coordination of DM or neutrino experiments, T. Ferber is a core developer of the Belle II analysis software framework, and T. Ferber and M. Klute have served as physics performance coordinator in collider physics experiments. All DELight members have contributed to data analyses. Joining the expertise of high energy physics and astroparticle physics software development will allow this RU to provide a state-of-the-art software framework using established standards for reconstruction software, automated data validation, and analysis code. F. Kahlhoefer is an expert for developing public likelihood functions for direct detection experiments [62] and their use in global fits [63], the reconstruction of DM parameters [64], and he addressed the response of direct detection experiments to LDM [65, 66]. Building on this work will be crucial to maximally exploit the science potential of DELight.

The expertise to successfully design, build and operate the superfluid He-based low-background DM detector DELight, using MMC detector technology, and to read, process and analyze its data to search for LDM and other DM candidates is entirely available within the proposed RU. Close collaboration is already established between the three institutions and highly beneficial facilities and infrastructures are accessible. This poses the **unique opportunity to realize a novel DM experiment with world-leading low-mass sensitivity with researchers from only three institutions**. DELight will further directly benefit from the extensive project management expertise available among the (co-)applicants, who served and serve in highly visible management roles in experimental collaborations and at their academic institutions.

2 Objectives and joint work programme

2.1 Objectives of the overall project and expected benefits of collaboration within the unit, incl. a description of the group composition and their project-specific qualifications

The central objective of this RU is to design, build and operate DELight, a new particle physics experiment with a world-leading sensitivity to directly detect LDM in a cryogenic superfluid ^{4}He target. So far, no dark matter search using superfluid helium has been conducted. The goal for phase-I of the RU is to conduct a first dark matter search with a limited exposure, which will cover previously unexplored parameter space and has a real chance for a dark matter detection. In parallel, research and development will be conducted for a possible phase-II, which will improve the sensitivity to LDM by more than two orders of magnitude.

A target with a low mass number, a low detector threshold and a low background level are

Table 1: Projects and project leaders within the proposed Research Unit. All projects and their close cooperation are required to realize DELight. (MMC = Magnetic MicroCalorimeter).

Project	Project Title	Project Leader
P1	Cryogenic setup and superfluid ^{4}He cell	Christian Enss
P2	MMC-based detection system	Sebastian Kempf
P3	Low-background environment	Marc Schumann
P4	Site and Infrastructure	Sebastian Lindemann
P5	Data acquisition and computing	Belina von Krosigk
P6	Science analysis	Kathrin Valerius

necessary for a search for LDM. Realizing DELight thus requires very different expertise and competences in low-temperature superfluid helium physics, low-threshold quantum sensing, low-background techniques, detector control, data acquisition and electronics as well as data analysis and physics interpretation, and can only be realized through the confluence of the six projects summarized in Tab. 1. These projects bring together the combined expertise of the members of the RU as listed in Tab. 2, together with their affiliation and research area of relevance for DELight. The contributions by both the project leaders and co-applicants to the various projects are described in the respective project descriptions, highlighting the synergy of the comprehensive expertise within DELight: most researchers are involved in several projects to bring in their expertise and ensure smooth communication between the different projects, which often even share physical interfaces. All researchers will contribute to project P6.

2.2 Joint work programme including proposed research methods

All six proposed projects of the RU work together towards a single common goal: the realization of DELight. The major challenges of such endeavor have been identified and will be addressed in the individual projects P1-P6. These will employ different research methods to meet their goals, however, it is important to emphasize that DELight can only be realized by the consorted efforts of all projects. The joint work program is shown in Fig. 5, with a plethora of intertwined and connected projects, which in most cases require contribution from several projects. A set of fundamental projects (P0.x) will be addressed jointly by all members of the RU, e.g., the detector operation including the first science run, as well as the analysis for the first dark matter search. It should be noted that, for risk mitigation, each work package listed in Fig. 5 includes contingency and that the programme includes a certain flexibility, reducing the impact of potential individual delays on the other projects and DELight as a whole. The projects and how they contribute to DELight are briefly described in the following. More details can be found in the individual project descriptions.

P1 Cryogenic setup and superfluid ^{4}He cell. [**Enss**, Gastaldo, Kempf, Schumann] Taking advantage from the broad experience in low-temperature, solid state and liquid helium physics, **P1** will develop, construct, commission and characterize the superfluid helium cell, including a film burner, a purification system, a level meter and a detector platform. This cell, with all its components will be integrated into a customized cryogenic platform which will be adapted to a new commercial dry dilution refrigerator. Design and construction of the cell will be done in close cooperation with **P2** and **P3**. The work on the cryogenic platform will be done in collaboration with **P2**, **P3**, **P4** and **P5**.

Table 2: Participating researchers from the three institutions: University of Freiburg (UFR), Heidelberg University (UHD), and Karlsruhe Institute of Technology (KIT). The table also lists the researcher's key research areas of relevance for this RU and the projects they will contribute to. (DAQ = data acquisition, DM = Dark Matter, HEP = High Energy Physics.)

Name	PhD	Institution	Research Area	Projects
Project leaders				
Prof. Christian Enss	1991	UHD	Cryogenic particle detectors, low temperature physics	**P1**, P2, P4, P6
Prof. Sebastian Kempf	2012	KIT	Quantum technology, cryogenic particle detectors, superconducting electronics	**P2**, P1, P6
Prof. Belina von Krosigk	2015	UHD	DM direct detection, DAQ and trigger systems	**P5**, P2, P6
Dr. Sebastian Lindemann	2013	UFR	DM direct detection, low-background methods, slow control	**P4**, P3, P6
Prof. Marc Schumann	2007	UFR	DM direct detection, low-background methods, DAQ systems	**P3**, P1, P4, P6
Prof. Kathrin Valerius	2009	KIT	Neutrino physics, DM direct detection, simulation and analysis tools	**P6**
Co-applicants				
Dr. Klaus Eitel	1995	KIT	Neutrino physics, DM direct detection, low-background methods	P3, P4, P6
Prof. Torben Ferber	2012	KIT	DM collider searches, trigger systems, reconstruction software	P5, P6
JProf. Loredana Gastaldo	2005	UHD	Cryogenic particle detectors, quantum technology	P1, P6
JProf. Felix Kahlhoefer	2014	KIT	DM phenomenology and cosmology, global fitting routines	P6
Prof. Markus Klute	2004	KIT	DM collider searches, DAQ systems, HEP software and computing	P5, P6

P2 MMC-based detection system. [**Kempf**, Enss, von Krosigk] The project will design, fabricate, install, calibrate, and operate the MMC-based wafer calorimeter system. This includes designing the wafer calorimeters and the dc-SQUID-based readout system, wafer calorimeter batch fabrication, mounting the individual calorimeter modules resembling the detector, integrating the modules into the helium cell, as well as characterizing the combined system of cell and calorimeters. **P2** will strongly benefit from its participants' background in solid state physics, superconducting electronics and cryogenic microcalorimeters. The design and integration will be done in collaboration with **P1**, the dc-SQUID-based readout system will be developed together with **P4** and **P5**.

P3 Low-background environment. [**Schumann**, Eitel, Lindemann] The project will ensure that DELight meets its low-background goals. By relying on the project members' expertise in the design and construction of low-background detectors, material selection and detector simulation studies, **P3** will develop a detailed detector model to study in Monte Carlo simulations the background

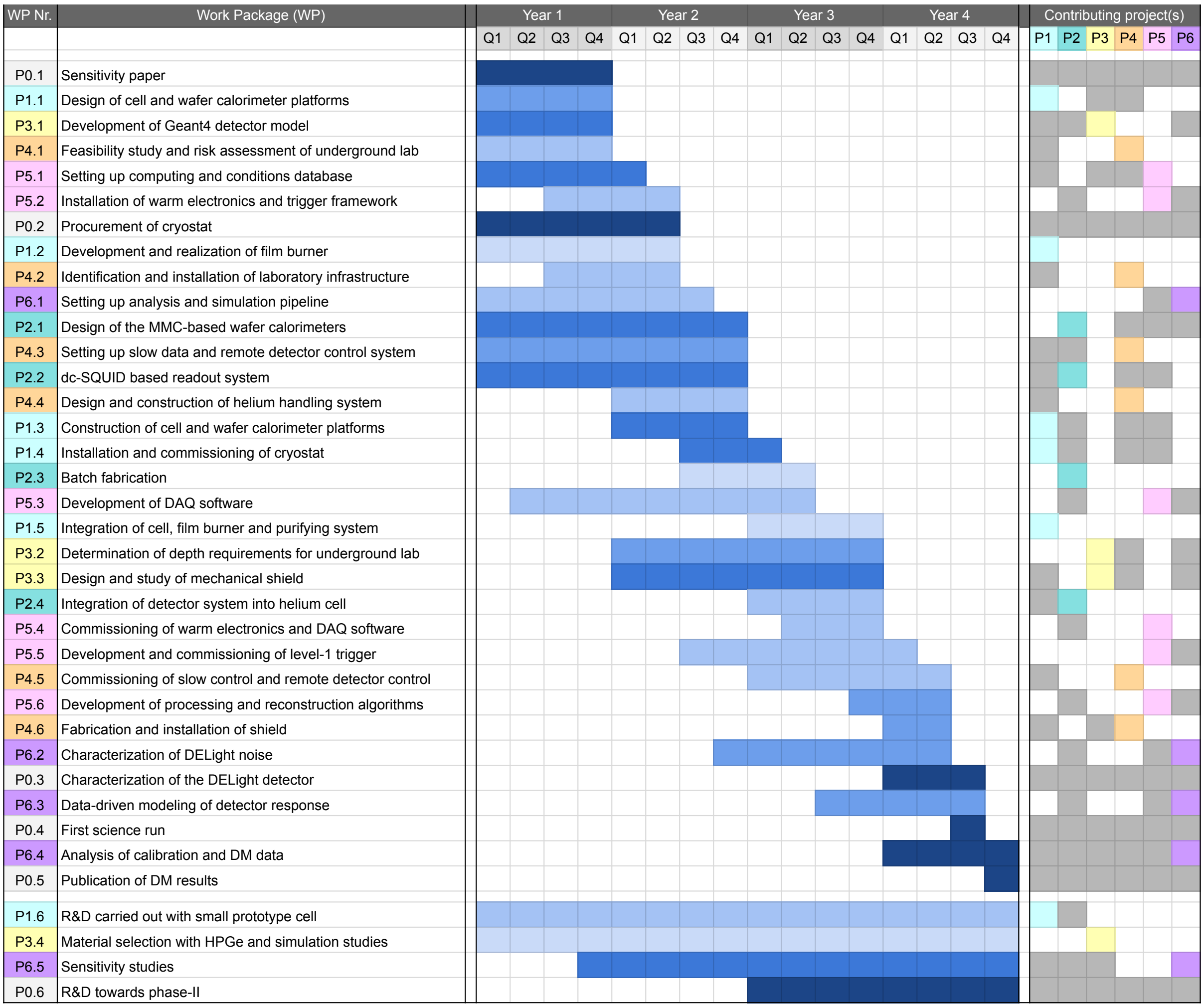

Figure 5: Summary of the joint DELight work program displaying the collaborative work flow of the projects P1 through P6. The work package (WP) numbers indicate the respective lead project and the count within that project's list of WPs. The P0 identifier is used for WPs that are equitably performed by all participants. The shades of blue within the timeline indicate the amount of contributing projects. The lightest blue is used for WPs only conducted within the respective lead project. The darkest blue is used for WPs to which all projects contribute. The rightmost block of the program signals the lead project (color) and the further contributing projects (gray).

level of the detector, taking into account measured material contaminations as well as the shielding including potential rock overburden. The simulation work will be done in collaboration with **P1**, **P2** and **P6**, and the studies on shielding rely on close exchange with **P1**, **P4** and **P6**.

P4 Site and Infrastructure. [**Lindemann**, Eitel, Enss, Schumann] The project will develop and contribute crucial components for the operation of DELight and a successful LDM search: the slow control system, the helium handling system and the radiation shield. P4 will also investigate and prepare for an underground operation of the detector. The work program will rely on ample of expertise in detector operation, both in surface and underground laboratories, and make use of a powerful slow control framework developed over the last years [67]. All of the work of **P4** will be done in close collaboration with **P1**; the slow control work will also involve **P2** and **P5**, and the work on the shield will be done jointly with **P3**.

P5 Data acquisition and computing. [**von Krosigk**, Ferber, Klute] The data acquisition (DAQ) and trigger systems, capable to achieve a very low threshold, as well as the computing system required to store the data and the simulations, and to provide them for analysis, will be designed and deployed by project P5. The work will make use of the broad expertise in terms of DAQ, (digital) electronics, high- and low-level triggering, as well as computing available within the project. As **P5** collects and stores data from the detector, it cooperates closely with **P6** on most topics. The computing system will be defined together with **P1**, **P3** and **P4**, while triggering, wafer calorimeter control and signal reconstruction require close exchange with **P2**.

P6 Science analysis. [**Valerius**, Eitel, Enss, Ferber, Gastaldo, Kahlhoefer, Kempf, Klute, Lindemann, Schumann, von Krosigk] The last project of the RU is responsible for setting up, coordinating and maintaining the software required for the full analysis chain of raw data to final inference analyses for LDM and other searches. The analysis chain is complemented by a simulation branch. The project relies on the breadth of data analysis and simulation expertise available within DELight, obtained in various projects in astroparticle and high-energy physics. As **P6** will prepare the data analysis chain it closely collaborates with **P5**, providing the data, in most tasks. The characterization of the detector response, including its noise, will be addressed jointly with **P2** and **P5**. **P3** will provide simulations modeling the radioactive background spectra. The calibration strategy will be determined in collaboration with **P1** and **P2**. The analysis of the calibration and science data will be a RU-wide effort.

Research and development towards DELight phase-II will be conducted in all six projects, again in close cooperation with all relevant partner projects to take into account their expertise and input.

2.3 Handling of research data

The main research data collected by DELight are amplitude time series stored in ROOT or HDF5 file format. The expected size of both the raw data and the simulated data is up to $\mathcal{O}(100)$ TB/yr, each. Automatic data quality monitoring during data taking will be used to ensure best data quality. All raw data will be stored at the KIT computing infrastructure with access limited to DELight collaboration members from institutes that have signed a collaboration agreement. High-level features extracted from the *raw data* are used for analysis after calibration procedures and clean-up data-selections. These *high-level analysis data* are significantly smaller in volume compared to raw data. The feature extraction, calibration procedures and data-selections will be documented and published in peer-reviewed, open-access technical journals. All software used for feature extraction and clean-up will be made available in a `gitlab`[1] repository under an open-source license like GNU Lesser General Public License (LGPL) or similar. All scientific results will be published in peer-reviewed scientific journals and in parallel on the free distribution service and open-access archive `arXiv`. It is furthermore planned to publish likelihoods and other supplementary information needed to reproduce the results. The RU will make high-level analysis data itself available to the scientific community upon qualified requests, after a three year embargo time. Analysis data, and all documentation required to use the data, will be published on `zenodo`[2] with digital object identifiers (DOI). According to the `zenodo` policies, these datasets will be available for the "lifetime of the host laboratory CERN, which currently

[1] https://gitlab.com
[2] https://zenodo.org

has an experimental program defined for the next 20 years at least". A DELight member will take the role of software- and computing coordinator and will be responsible for all questions related to data handling at DELight. In addition to all aforementioned measures, the three involved institutions offer research data management support and long-term archiving solutions in compliance with their policy on handling of research data and the corresponding DFG guidelines.

2.4 Potential impact on the research area and local research environment; distinction from other ongoing programmes directly related to the research topic

Impact on the research area. Over the past few years, LDM has garnered increasing interest within the dark matter research community. The combination of its lightweight target material and outstanding energy resolution positions DELight to be at the forefront of these efforts. Currently, several experiments are gaining momentum with the objective of exploring this specific parameter space (see below). However, DELight possesses the capability to take a leading role in this research, enabling the probing of dark matter masses down to the sub-100 MeV scale in DM-nucleus scattering interactions with cross sections well below $10^{-33}\,\mathrm{cm}^2$, where shielding by the atmosphere and earth becomes negligible [11]. This potential breakthrough could make DELight the first to achieve a groundbreaking discovery in the elusive quest for dark matter. In addition to these possible, groundbreaking results, DELight will contribute to several state-of-the-art R&D efforts. Magnetic microcalorimeters are state-of-the-art cryogenic radiation detectors with unparalleled energy resolution [47,48]. Within DELight they will be coupled to large-area silicon, sapphire or silicon-on-sapphire wafers. The advancements in this technology that will occur within the context of DELight will benefit particle detection in a variety of other fields allowing the realization of experiments that not have been thought possible so far. DELight furthermore aims to demonstrate that a DM detector based on superfluid helium can potentially reconstruct the directional information as e.g. imprinted by the impinging dark matter particle [42]. Utilizing this directional information, it may pave the path to surpass the otherwise constraining neutrino floor [29, 43, 44]. Another R&D project anticipated for phase-II of DELight, is the exploration of the use of electric field ionization to enhance the sensitivity of superfluid helium dark matter detectors, as proposed by [41]. Historically, advancements in detector technologies and detection techniques have always helped the field to advance in general. This RU will thus not only directly contribute to the exclusion, or potentially even confirmation, of dark matter models but also to the progress of low-threshold detection field in general.

Impact on the local research environment. The proposed RU will bring together researchers from UFR, UHD, and KIT. The team makes use of the geographical proximity of these sites through the joint assignment of project tasks, as outlined in Secs. 2.2 and 7. While this distribution of work benefits DELight, drawing on the specific expertise available in the contributing groups, it simultaneously contributes to shaping and developing the local research environment in the long term. All three institutions already have established research areas in direct DM detection (see also Sec. 1), but with DELight the proposed RU will expand the local research to LDM searches in the newly accessible range of light masses using state-of-the-art technologies. Entering this new experimental area opens up exciting links between the research groups at the participating institutions with their respective specialization (such as (astro)particle physicists, phenomenologists, and experts in superfluid helium technology and quantum sensing development, for instance) – a development which is supported further by several recent hires at the partner universities.

Notably, while contemporary efforts to search for DM are usually embedded in sizeable, multinational collaborations, DELight is an experiment which will be realized entirely within the proposed RU. This gives the participating institutions the opportunity to conduct a high-impact DM experiment locally, at comparably moderate cost. A desired effect of the RU is a structural impact both on the research portfolio of the individual partner institutions and on the local network among the three participating universities in Baden-Württemberg.

DELight utilizes expertise and facilities from the different sites, such as HSS (see Secs. 1 and 2.6), or the VdA underground laboratory (see Sec. 2.6). Moreover, the proposed work draws on special knowledge on computing, analysis methods, and data science available in the local (astro)particle physics groups. In turn, DELight offers graduate students specializing in these topics a fruitful work environment to apply and deepen their skills. A particular strength of the RU is its composition of both physicists and researchers from electrical engineering. The direct intertwinement of these fields will not only benefit DELight, but will also create lasting synergies impacting the local research environment. The KIT Center Elementary Particle and Astroparticle Physics (KCETA) with its associated graduate school (KSETA) forms an ideal umbrella for such cross-over activities, and DELight will complement and strengthen the research activities of the center. At UFR and UHD DELight will similarly connect with existing structures such as the RTGs 2044 "Mass and Symmetries after the Discovery of the Higgs Particle at the LHC" and RTG 2058 "HighRR" and their planned successors, respectively. Doctoral researchers working on DELight will be members of these graduate schools and thus contribute valuable new impulses to the established research programs.

Distinction from related research projects and competition. Over the last years, LDM has gained increasing attraction to the DM community [19]. A number of direct detection projects have placed constraints on LDM even though decreasing DM masses increase the challenge to observe DM interactions with the target material. Direct detection projects such as the solid state experiments CDEX [68], CRESST [69], EDELWEISS [70], SuperCDMS [71,72] and the liquid noble gas experiments DarkSide [73], LZ [74], PandaX [75], and XENON [6] have made significant progress in lowering their detection threshold, a requirement to be sensitive to lighter DM masses. Only very few of the searches, e.g., CRESST-III [69] and SuperCDMS [11,76], were able to demonstrate direct sensitivity to sub-GeV DM in standard **elastic DM-nucleus scattering** searches, though. CRESST-III achieved this with a dark matter target consisting of a 26.6 g $CaWO_4$ crystal and a nuclear recoil threshold of 30.1 eV and SuperCDMS used a 10 g and a 1 g Si crystal with a threshold of 16.3 eV and 9.2 eV, respectively. However, all three searches are subject to atmosphere and earth shielding which is limiting the mass reach, given the high, probed cross sections.

Taking into account inelastic DM-nucleus scattering interactions including secondary effects, such as the Migdal effect [77] or Bremsstrahlung [78], allowed all of the above-mentioned experiments to probe sub-GeV DM masses. The results, however, bear notably higher uncertainties, including the fact that the Migdal effect itself has not yet been observed in nuclear scattering events [79]. Ultimately all aforementioned experiments are intrinsically limited by the mass of the used target nuclei (Ar, $CaWO_4$, Ge, Si, Xe), which are notably heavier than any sub-GeV DM candidate, rendering the energy transfer in a scattering event extremely inefficient: If the DM particle becomes too light compared to the nucleus, the signature becomes too small to be observed.

Several experiments also search for **DM-electron scattering** mediated by a new particle [80]. The signature is experimentally beneficial as the scattering partner, the electron, is notably lighter than the one in nucleus scattering events and can lead to detectable electron recoil signals above the threshold. In addition the electron recoil signal is less affected by quenching effects. Experiments such as DAMIC [81], SENSEI [82], and SuperCDMS-HVeV [83, 84] use Si as target material and measure the charge released from its bound state as a result of the initial energy deposition. Liquid noble gas experiments such as DarkSide (Ar) [85], PandaX (Xe) [86, 87] or XENON (Xe) [88, 89] probe DM-electron interactions in dedicated "charge-only" analyses [90] which are systematically less clean than their standard "light+charge" approaches as many of their standard background reduction methods as well as signal corrections are not applicable.

The intrinsic limitation of the current DM-nucleus scattering experiments, imposed by the mass of the target nuclei in combination with relatively high energy thresholds, motivates the use of targets made from notably lighter elements. There are currently three projects following this approach: **NEWS-G** [91] (mainly Canada and France) uses gaseous targets of helium or hydrogen (in gas mixtures like Ne-CH_4) in a large spherical proportional counter. Using several light target gases allows for the optimization of momentum transfer for a given LDM mass range to be probed. The disadvantage of a gaseous target is its low density and thus the reduced probability for a DM interaction which scales with the number of scattering partners. A larger spherical detector of 3 m diameter and a reduced background, called DarkSPHERE, is being proposed to search for LDM above 50 MeV/c^2 [92].

The **ALETHEIA** experiment [93] (China) plans to use liquid He as target in a dual-phase TPC operated at $\sim$ 4 K, following the successful approach of liquid noble gas TPCs using the heavier targets Xe and Ar. However, $\sim$ 42 eV are required on average to create an electron-ion pair. This is rather high and counteracts the advantage of the light target nucleus if scintillation and ionization are the only measured signal channels. At nuclear recoil energies below $\sim$ 10 keV most of the recoil energy is transferred to quasiparticles [22] that are only observable by calorimetric detectors operated at mK-temperatures. Such detectors are sensitive to all signal channels shown in Fig. 2 and are thus able to exploit the full potential of a He target. The only two projects following this approach, taking advantage of the quasiparticle signal channel, are DELight and HeRALD. While DELight will instrument the He cell with MMCs and use a film burner to keep the absorber surfaces in vacuum helium-free, the strategy of **HeRALD** [22] (USA) is to use microcalorimeters based on transition edge sensors (TESs) and Cs-based film blocking. HeRALD is currently in its design and R&D phase [94] having first results on the superfluid helium light yield [95] and first quantum evaporation data. Using a $\sim$10 g superfluid He target, HeRALD recently successfully demonstrated the use of a heat-free film-blocking method employing an unoxidized Cs film to prevent a helium film on the calorimeter, and measured the quasiparticle channel gain of their detector prototype [33].

In the search for LDM-nucleus scattering with LDM masses below 500 MeV no other project competes with DELight at the same level as HeRALD. While both will detect the scintillation signal and in addition exploit the quasiparticle channel, the envisaged technical realizations are quite complementary, which will be beneficial for the future of the field. There are two important differences: While HeRALD will prevent the superfluid He film creeping onto the calorimeter (and significantly worsen its performance) by means of unoxidized Cs, essentially the only known material that is not wetted by He and which thus effectively blocks the He flow [96], DELight will implement a film burner for the same purpose [32]. While the film burner will add an extra heat load to the detector, it is easier to operate compared to the application of a Cs layer, especially in view of reliability and repeatability, and will greatly simplify the R&D phase where repeated detector openings are expected. It has already been successfully demonstrated by HERON. The second important difference between HeRALD and DELight is the sensor: HeRALD intends to use calorimeters made from a Si wafer instrumented with an array of tungsten transition-edge sensors (TES) to sense athermal phonons in the Si [97] while DELight will employ MMCs (see above and P2). Both sensor types are promising approaches and these complementary R&D paths happening in parallel will be instrumental for identifying the best path forward.

2.5 Measures to advance research careers

The integration and promotion of early-career researchers will be a key aspect of the proposed RU. The main objectives in this respect are the systematic support of doctoral and presearchers, and habilitation candidates taking advantage of the dedicated entities at UFR, UHD, and KIT. All Doctoral researchers will have the opportunity to become a member of one of the graduate schools at a contributing university which support training in technical skills and provide a network of peers working in the same research area (see Sec. 2.4). To give a few explicit examples of the established and available support structures at all three universities: At **KIT**, young researchers have access to the Karlsruhe House of Young Scientists (KHYS), the central institution for supporting early-career researchers providing an extensive portfolio of personal skills training, as well as comprehensive support measures regarding internationalization, networking, and career orientation. Furthermore, the KIT “Young Investigator Group Preparation Program” (YIGPrepPro) offers postdocs who aspire to acquire a third-party funded junior research group professional mentorship, tailor-made proposal advice, and an individual training program as well as a network of current young investigator group leaders. **UFR** has established the International Graduate Academy (IGA) and the Department of Equality Diversity and Academic Career Development, both of which offer targeted counseling, qualification, coaching and mentoring services for young researchers, which together help improve the boundary conditions for academic qualification. Through workshops, coaching, training, and networking events, these institutions offer a comprehensive range of support for early career researchers on career-relevant topics and skills, including management, leadership, mental health, communication, publication, career planning, and language skills as well as the development of good research practice and learning about the acquisition of third-party funding. **UHD** has set up structures to ensure excellent conditions for doctoral researchers and early career researchers, like the “Quality assurance and quality development for doctoral researchers” program (heiDOCS), the Graduate Academy (GA) which is the central coordinating institution for the support and fostering of doctoral researchers and postdocs, and programs like heiTRACKS and heiSKILLS, which offer a rich spectrum of mentoring and coaching opportunities for doctoral and postdoctoral researchers, and students. Doctoral researchers are further supported by the Graduate Academy and at the department level by the Heidelberg Graduate School for Physics (HGSFP).

Early-career researchers will be integrated in the teaching at their university and their presence as speaker at national and international conferences will be given a special focus. Visibility within the community and networking is one of the key aspects of successful career pathways.

2.6 National and international cooperation and networking

The applicants of the proposed RU are members of several international collaborations, like XENONnT, KATRIN, SuperCDMS, AMoRE, ECHo and others. The research program of the proposed RU will profit from cooperations and networking with members of these collaborations.

In addition, the proposed RU is in close contact with a world-wide community of low-background experts and screening facilities for the selection of radiopure materials. Through M. Schumann and S. Lindemann the RU has access to the VdA laboratory via the Albert Einstein Center for Fundamental Physics and the Laboratory for High-Energy Physics (LHEP) of at the University of Bern. For radiogenic assessment of bulk materials, complementing the γ-spectrometry measurements, DELight has access to the inorganic mass spectrometry facility [98] at the Gran Sasso National Laboratory, Italy, with outstanding expertise in inductively-coupled plasma mass spectrometry (ICP-MS), and to neutron activation analysis, e.g., at the Paul Scherrer Institute in Switzerland. High sensitivity surface alpha counting using a XIA UltraLo-1800 alpha counter can be done in cooperation with colleagues at the underground laboratory at Kamioka, Japan [99].

Besides that, S. Kempf and C. Enss are affiliated with the HSS center a nationally unique production and characterization center for High-resolution Superconducting Sensors, presently being built up at KIT (see Sec. 1) by a collaboration of three institutes: the Institute for Data Processing and Electronics (IPE), the Institute of Micro- and Nanoelectronic Systems (IMS), both KIT, and the Kirchhoff-Institute for Physics (KIP) at UHD. It addresses the ever-increasing demand for large-scale cryogenic sensor systems making it a key facility in bringing these types of detector systems to the next level of technological readiness. It will provide production and characterization capabilities for detector systems with several thousands and even millions of individual sensors, and will thus enable to build the DELight detector that will ultimately consist of several thousands of individual sensors, simultaneously operated and read out using dedicated superconducting electronics. The first stage of HSS is scheduled to complete mid 2023, the second stage is scheduled for mid 2025. This schedule fully aligns with the schedule of the proposed RU.

2.7 Collaboration with international cooperation partners – Does not apply.

2.8 Description of the spokesperson's qualifications

The following description will provide my, Belina von Krosigk's, personal motivation, project leadership experience, and scientific qualification to assume the role of spokesperson for this RU.

Personal motivation. The motivation behind all my research work is the question of what particles DM is made of, one of the core questions of modern physics. I have specialized in direct searches, among other things because they directly probe the DM content of our universe, an exciting aspect of these searches. It is my firm conviction that the picture of a single DM particle is too simple and that DM is just like ordinary matter composed of matter particles and mediators, which together form the so-called dark sector. In this expanded picture, DM particles may be much lighter than is measurable with current direct search methods of recent decades and new approaches are needed. New approaches are thus a key focus of my research since several years. I wish to take on the role of the spokesperson of DELight, because the research goal of DELight is completely in line with my research goals and the project is feasible in a collaboration of only three institutions that are geographically close to each other and with which I am already in a lively and fruitful scientific exchange. DELight offers us an opportunity that I want to seize and implement together with all members of the RU.

Experience in project leadership. I have been awarded a DFG Emmy Noether Junior Research Group Leader position in 2019 and have since then managed the group and project. The project is in its second funding period after a positive evaluation of the first funding period in 2022. I have further been in several leadership positions within the SuperCDMS Collaboration. These positions include project manager of the DAQ and trigger software within the US Department of Energy (DOE) line management of the SuperCDMS project, DAQ and trigger operations coordinator, and elected member of the SuperCDMS Executive Committee which is the top-level management of the SuperCDMS Collaboration.

Scientific qualifications. I have been working on low-background, rare-event search experiments since 2010, starting with the SNO+ neutrino experiment, and have specialized on direct DM searches since 2015, when I joined the SuperCDMS Collaboration, one of the world's leading international collaborations on low-mass DM searches. In both cases, SNO+ and SuperCDMS, I have been or am a collaboration member during the construction phase of the experiment and have thus gathered years-long experience in building rare-event search detectors which includes taking critical decisions in the process as new challenges and road blocks occur. At the same I had access to science grade SuperCDMS data at all times both from the last generation of the SuperCDMS experiment and from R&D devices called SuperCDMS-HVeV. These data allowed me to pioneer searches for LDM candidates and for dark photons within the SuperCDMS Collaboration. The main goals of my Emmy Noether project are direct DM searches beyond the standard WIMP with, and upgrading the DAQ and trigger system of, SuperCDMS at SNOLAB. All these experiences are of direct relevance to DELight and provide critical scientific qualifications to lead this RU.

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4 Coordination

4.1 Description of how joint objectives and the joint work programme will be implemented in the Coordination Project

The overall objective of the proposed RU is to search for LDM in the sub-GeV mass range by building a new superfluid helium detector. To achieve this, all six projects must work closely together. This requires an overarching structure in which the projects are embedded and which coordinates the efforts. There are several elements that are part of the Coordination Project that will enable this:

Administration. An overall work program has been established (see Fig. 5), which is steered and monitored via the Coordination Project. For this purpose, a governance structure was established, which is shown in Fig. 6. Several imported tasks of the work program (P0.1-6) intentionally do not have a lead project, as they are an expression of the necessary close collaboration within the RU. These will be managed and monitored as part of the Coordination Project. In addition, the administration will be responsible for the coordination funds. It monitors and enforces the equal opportunity measures, organizes reports, publications and contributions to conferences.

Large-scale instrument. The proposed RU requires a central large-scale instrument, the funding for which is requested within the Coordination Project. It comprises of two parts: a cryogenic platform, holding the DELight dark matter target, and a multi-channel SQUID system for readout. The central large-scale instrument will be shared and used by all projects.

Meetings and operation shifts. To promote inter-project collaboration and information exchange among all participating scientists, in-person collaboration meetings are held twice a year. In addition,

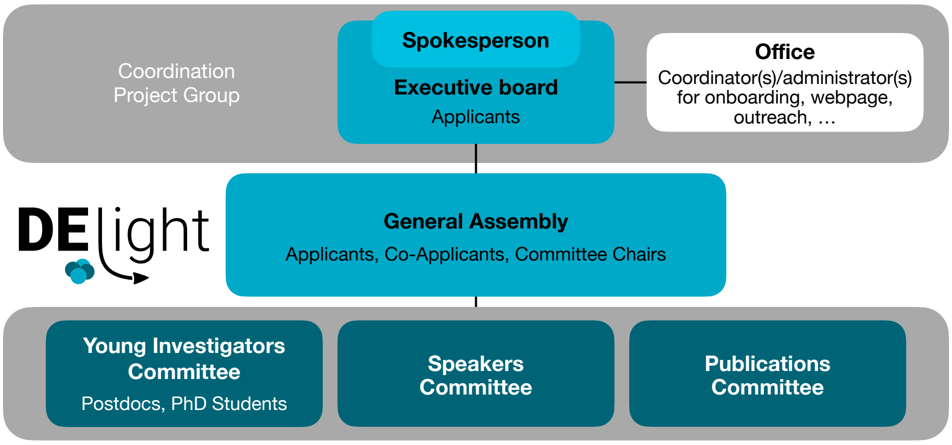

Figure 6: Embedding of the Coordination Project Group within the governance structure of the DELight Research Unit.

work shifts will be carried out during the operation of the DELight detector. All projects will participate in this. They will be organized within the framework of the Coordination Project.

Coordination meetings online. A research program involving several groups requires regular meetings to discuss coordination issues. The DELight Executive Board will meet for this purpose at least monthly online.

4.2 Requested modules

Three modules are requested within this proposal. Those are the modules Coordination, Network Funds, and Standard Allowance for Gender Equity Measures. The justification for, and costs within, each module are summarized in the following. All values in this section are rounded to the nearest hundred euros. A summary of the costs of both the individual projects and the Coordination Project is provided in Tables 4 and 5, respectively.

4.2.1 Coordination Module

Coordination funding

The total cost estimate over the funding period of four years is **54,300 €**.

Support staff: The coordination and administration of purchases, outreach events, in-person meetings and all other administrative duties including maintaining the RU web page will be done by a part-time (25%) administrator/secretary at TV-L E9, i.e. 0.25 x 54,300 € = 13,600 € per year.

Gender inclusion funding for spokespersons

The total cost estimate over the funding period of four years is **320,000 €**.

The spokesperson, Belina von Krosigk, is within the group of underrepresented female professors in the field of physics. To reduce the additional workload of the RU spokesperson we request 80,000 € per year for the entire funding period. These funds will be mainly used for a part-time administrator/secretary, traveling, and a temporary teaching substitute for periods during which the project will require the undivided attention of the spokesperson.

4.2.2 Network Funds Module

Direct project costs

The total cost estimate over the funding period of four years is **67,400 €**.

Collaboration meetings: In addition to standing weekly or bi-weekly virtual meetings, in-person collaboration meetings are planned to take place twice a year. In-person work-visits will be funded by the travel costs requested by the individual projects. The collaboration is formed by the six project leaders, the five co-applicants, two and a half postdoctoral researchers on average, and seven doctoral researchers. The collaboration meeting venue will rotate between the three RU member institutions. Travel and accommodation will thus only be required for two thirds of the collaboration on average. Catering will be required for all members equally. The respective total costs over four years are estimated to amount to **25,000 €**.

Detector transport: After a first successful surface run, the RU plans to move the DELight detector to the VdA underground laboratory. This may already be possible during the first funding period of this project in which case funding for moving the experiment will be required. The respective total costs are estimated to amount to **5,000 €**.

Operations shifts: During operations of the experiment to acquire calibration and science data, the presence of shifters on site is necessary. This is true for all potential sites at which DELight will eventually be operated, on surface or underground. A typical length of a shift is 7 days at an estimated cost of 1,100 €. We anticipate that two shifts per person funded via the RU ($2 \times 11 \times 1,100$ €$=$ $24,200$ €) and per applicant ($2 \times 6 \times 1,100$ €$= 13,200$ €) are required in year 4. This adds up to **37,400 €**.

The Institute of Physics at UFR will support the proposed RU with at least 20,000 € seed funding, e.g., to cover possible operation costs at the VdA underground laboratory.

Large-scale instrumentation

The total cost estimate over the funding period of four years is **1.2 M€**.

The cryogenic platform, the central element for the proposed DELight experiment, is a powerful ^{3}He/^{4}He dilution refrigerator as specified below. It is not assigned to an individual project but is available to the entire RU within the Coordination Project. Only the collaborative use of the cryostat by all members of the RU allows to exploit the full potential of the science to be conducted within DELight. All costs for the basic operation and maintenance of the cryostat are covered by Heidelberg University as hosting institute. Access to local workshops, technicians, and engineers is provided at all three DELight member institutions.

The required large-scale instrument consists of a cryogenic platform with readout electronics, as described here.

Cryogenic platform: a commercial pulse-tube cooled ^{3}He/^{4}He-dilution refrigerator is foreseen to be used in DELight. The DELight detector needs be operated at low millikelvin temperatures. The cryogenic platform foreseen for the DELight detector is a commercial pulse-tube cooled $^3He/^4He$ dilution refrigerator. These highly reliable cryostats are available in a wide range of cooling powers and achieve base temperatures below 10 mK. In addition, they have a duty cycle of nearly 100% due to their cryogen-free operation. The cryostat for DELight will require some important customizations such as a particularly high cooling power around 300 mK necessary for the film burner operation. We have discussed this particular need with several manufacturers of such dilution refrigerators, and the best solution is to run two independent dilution units in one cryostat. In this way, the unit for the film burner can run at a high circulation rate and provide the required cooling power, while the other unit cools the cell and wafer calorimeters at very low temperatures. All other solutions require to compromise on the lowest possible temperatures for the cell and the detectors, which would significantly impair the overall sensitivity. To handle the associated throughput for both units and to heat sink the wiring of the readout system, pulse tubes with large cooling powers are needed. In addition, the incorporation of low-activity cold lead and copper shields should be possible. The estimate for the total cost is **1,092,700 €** (incl. VAT).

The required ^3He-^4He mixture listed as items 2 and 6 of the attached quote is not included in these costs. The ^3He-^4He mixture, costing 392,700 € (incl. VAT), will be funded by the UHD Kirchhoff-Institute for Physics as seed funding.

Multi-channel dc-SQUID electronics: For simultaneously running all wafer calorimeters of the DELight detector, a dedicated fifty-channel dc-SQUID electronics with flux locked loop (FLL) is required. To keep the costs at an affordable level, we aim for a multi-channel SQUID system with reduced range of functions and parameters as compared to state-of-the-art high-performance dc-SQUID electronics for R&D purposes. The budgeted electronics will hence be a crate-based system that can be equipped with up to 108 individual FLL channels, out of which fifty will be assembled in phase-I. Moreover, it will allow for uninterrupted battery operation to minimize disturbances from power lines, will be fully EMI shielded and will be easily upgraded to potentially double the number of channels at moderate costs. The estimate for the total cost of this electronics is **108,000 €** (incl. VAT), i.e. the budgeted electronics cost less than half of fifty state-of-the-art high-performance dc-SQUID electronics.

4.2.3 Standard Allowance for Gender Equity Measures Module

The total cost estimate over the funding period of four years is **60,000 €**.

The DELight collaboration is committed to diversity and equal opportunity as an essential component of science. Collaborative science flourishes under the inclusion of all people, bringing in their full identities, with the inclusion of underrepresented groups, and under the respect for family life. In this context DELight profits from a multitude of equal opportunity services offered by the three universities involved. Among the offered services are day-care centers, nursery schools, after-school care clubs and short-term child care, equal opportunity offices or an ombuds-woman for help with female specific problems, and financial support for scientists re-entering work. Special support for DELight female graduate students is offered through existing graduate schools by funding attendance of conferences, bridging stipends, financial help for child care or the possibility of hiring a student assistant to help with experimental tasks during pregnancy.

In 2021, the average proportion of female doctoral researchers in physics was 28 % (UHD) / 20 % (KIT) / 19 % (UFR), and the share of tenured female professors amounted to about 14 % at all three universities. Within DELight 33% of the project leaders, and 27% of all contributors identify as women. Apart from professor-level, there is no significant drop-out visible over the last years in physics at the three universities. We draw two conclusions from this: On the one hand, existing measures must be kept to ensure a stable fraction from student to postdoc level. And on the other hand we consider the overall fraction of people identifying as women in physics too low. For this reason, DELight is making every effort to reduce any bias in terms of gender, race, sexual orientation etc. in the hiring processes by raising awareness of mental shortcuts via providing unconscious bias training of the hiring committee members, and by making all steps of the hiring process transparent by publishing ranking criteria in advance and by providing application statistics. DELight will strive to provide an adequate research environment and a respectful corporate culture for all researchers.

Concrete measures to improve equal opportunities in the planned RU are compatibility of all DELight activities with a family schedule, flexible working times, and the offer of part-time contracts for scientists with responsibilities for care-dependent family members at any age. The RU will financially support scientists traveling to conferences with young children and provide the possibility of hiring a student assistant to help with experimental tasks during pregnancy, if not covered through aforementioned graduate schools. To increase the number of incoming students that identify non-male DELight will actively contribute to outreach activities at high-schools. For the implementation of these measures **15,000 € per year** are requested.

5 Project requirements

5.1 Employment status information

All project leaders have guaranteed positions throughout the duration of the funding period. Christian Enss, Sebastian Kempf, Belina von Krosigk, Marc Schumann, and Kathrin Valerius are each holding a full professor position (C4 or W3) at their respective institution. Sebastian Lindemann is currently holding a fixed-term researcher position (E13). The promotion to a permanent institutional scientific position (E14) at the University of Freiburg is currently ongoing. The process will be completed at the anticipated start date of the RU.

5.2 Composition of the project group

The group of persons working on the Coordination Project consists of all six applicants (see Tab. 3), forming the Executive Board, and the part-time administrator(s) requested within the Coordination Module. The spokesperson will chair the Executive Board and serve as Project Manager in consultation with the board. The Coordination Project group is embedded within the governance structure of the RU, as displayed in Fig. 6, and is responsible for the top-level coordination of the RU. The project group is in direct contact and permanent exchange with the General Assembly of DELight which comprises not only the applicants, but also all co-applicants, and the chairs of the Young Investigators, Speakers, and Publications Committees.

Initially the overlap between the group of (co-)applicants on the one hand, and the Speakers and Publications Committee, on the other hand, will be almost complete. But as the DELight

Collaboration grows, a more diverse filling of the various committees and positions is expected and actively sought. The positions of the General Assembly chair and committee chairs have a tenure of two years and will be rotated. Also, an ombuds group within DELight is anticipated, once the collaboration has reached a size that is notably larger than the group of applicants and co-applicants. This will be in addition to the ombuds offices that are available at all three participating institutions and which are already available to all members of the RU and the DELight Collaboration.

Table 3: Individuals who will work on the Coordination Project but will not be paid out of the project funds. This list of people forms the Executive Board.

Name and academic title	Employment status	Institution	Type of funding
Prof. Dr. Christian Enss	Full professor (C4)	UHD	institutional
Prof. Dr. Sebastian Kempf	Full professor (W3)	KIT	institutional
Prof. Dr. Belina von Krosigk	Full professor (W3)	UHD	institutional
Dr. Sebastian Lindemann	Staff scientist	UFR	institutional
Prof. Dr. Marc Schumann	Full professor (W3)	UFR	institutional
Prof. Dr. Kathrin Valerius	Full professor (W3)	KIT	institutional

5.3 Researchers with whom you have agreed to cooperate on this project

– Does not apply.

5.4 Scientific equipment

Grid Computing Centre Karlsruhe (GridKa) and Steinbuch Centre for Computing (SCC). The Steinbuch Centre for Computing (SCC) provides a wide range of computing and basic IT services for all KIT members as well as federal services for universities in the state of Baden-Württemberg, such as UFR and UHD, and for national and international projects, such as DELight. These services include the development platform `GitLab` which allows for collaborative and central version controlled software development. DELight already uses, and will continue to use, `GitLab` at KIT to develop, secure, and operate its software.

5.5 Project-relevant cooperation with commercial enterprises – Does not apply.

5.6 Project-relevant participation in commercial enterprises – Does not apply.

5.7 Researchers with whom you have collaborated scientifically within the past three years

The following list contains permanent researchers with whom at least one project leader or co-applicant has actively collaborated. We have omitted doctoral and postdoctoral researchers, permanent researchers from our own institutions and scientists with whom we have co-authored publications (such as community reports and collaboration publications) without any actual collaboration.

- Prof. Elena Aprile - Columbia University
- Prof. Csaba Balázs - Monash University

- Prof. Laura Baudis - University of Zurich
- Dr. Jörn Beyer - PTB Berlin
- Prof. Torsten Bringmann - Oslo University
- Prof. Marcus Brüggen - Hamburg University
- Prof. Silke Bühler-Paschen - TU Wien
- Prof. Ranny Budnik - Weizmann Institut of Science
- Prof. Auke-Pieter Colijn - Nikhef/University of Amsterdam
- Dr. Eddy Collin - CNRS Grenoble
- Prof. Jan Conrad - Stockholm University
- Prof. Patrick Decowski - Nikhef/University of Amsterdam
- Prof. Christoph Düllmann - University of Mainz
- Prof. Enectalí Figueroa-Feliciano - Northwestern University
- Dr. Stephan Friedrich - LLNL
- Prof. Luca Grandi - University of Chicago
- Prof. Pertti Hakonen - Aalto University
- Prof. Richard Haley - Lancaster University
- Asst. Prof. Yonit Hochberg - Hebrew University of Jerusalem
- Prof. Beda Hofmann - University of Bern
- Asst. Prof. Ziqing Hong - University of Toronto
- Prof. Josef Jochum - University of Tübingen
- Dr. Dr. Oliver Kieler - PTB Braunschweig
- Prof. Yong-Hamb Kim - CUP, IBS
- Prof. Michael Krämer - RWTH Aachen University
- Asst. Prof. Eric Kuflik - Hebrew University of Jerusalem
- Dr. Martin Loidl - CEA Saclay
- Prof. Kaixuan Ni - UC San Diego
- Prof. Uwe Oberlack - University of Mainz
- Prof. Scott Oser - University of British Columbia
- Prof. Jukka Pekola - Aalto University
- Prof. George Pickett - Lancaster University
- Asst. Prof. Matt C. Pyle - University of California Berkeley
- Dr. Matias Rodrigues - LNHB Saclay
- Prof. Joel Sander - University of South Dakota
- Dr. Kai Schmidt-Hoberg - DESY
- Prof. Torsten Schumm - University of Wien
- Prof. George Seidel - Brown University
- Dr. Peter Skyba - Kosice
- Dr. Tommaso Spadaro - INFN Frascati
- Prof. Thomas Stöhlker - Helmholtz Institut Jena
- Prof. Ronny Stolz - IPHT Jena
- Asst. Prof. Chris Tunnell - Rice University
- Prof. Christian Weinheimer - University of Münster

- Prof. Klaus Wendt - JGU Mainz
- Prof. Martin White - Adelaide University
- Prof. Michael Wurm - University of Mainz
- Prof. Kai Zuber - TU Dresden
- Prof. Dominik Zumbuhl - Universität Basel

6 Other Information

For convenience, all costs from the Coordination Project and the individual projects P1-6 are summarized and listed in Tables 4 and 5, respectively. **Not listed are any costs that are covered by KIT, UFR, and UHD as seed funding in support of the proposed RU. The total seed funding provided by the three institutions sums up to about 486,600 € on top of the own share for a small R&D dry dilution refrigerator as discussed in Project 2.**

Table 4: Summary table of the costs for the individual projects P1-6. The estimated costs are given in €. The personnel costs are according to the DFG Personnel Rates for 2023. PD stands for Postdoctoral researcher, PhD stands for doctoral researcher.

	Personnel	Equipment	Consumables	Travel	Other	Investments (> 10 k€)	Total
P1	1 PD (4 yrs), 0.5 PhD (75 %, 4 yrs) 542,700	-	32,000	17,400	-	42,000	634,100
P2	1 PD (2 yrs), 2 PhD (75 %, 4 yrs) 604,800	20,000	83,000	25,500	-	51,000	784,300
P3	0.5 PD (4 yrs), 1 PhD (75 %, 4 yrs) 382,500	-	45,000	32,600	-	-	460,100
P4	0.5 PD (4 yrs), 1 PhD (75 %, 4 yrs) 382,500	94,000	-	32,600	-	-	509,100
P5	0.5 PD (4 yrs), 1 PhD (75 %, 4 yrs) 382,500	8,000	-	15,200	-	22,500	482,200
P6	0.5 PD (4 yrs), 1 PhD (75 %, 4 yrs) 382,500	-	-	15,200	-	-	397,700
Total	2,677,500	122,000	160,000	138,500	-	115,500	**3,213,500**

Table 5: Summary table of the costs for the Coordination Project. The estimated costs are given in €.

Coordination Module	Cost
Coordination funding	54,300 €
Gender inclusion funding for spokespersons	320,000 €
Total	374,300 €
Network Funds Module	
Direct project costs	67,400 €
Large-scale instrumentation	1,200,700 €
Total	1,268,100 €
Standard Allowance for Gender Equity Measures Module	
Measures for gender equity funding	60,000 €
Total	60,000 €
Grand total	**1,702,400 €**

7 Project Description - Project Proposals

All six project proposals are directly appended to the overall description of the RU and the coordination proposal for the ease of reading. In compliance with the DFG guidelines, each project proposal is stand-alone with its own bibliography and page count. Given the strong connection between the projects there are, however, cross-references between the projects and towards the Coordination Project, which are indicated clearly.

P1 - Cryogenic setup and superfluid helium cell

Applicant: Christian Enss (Heidelberg)

Co-applicants: Loredana Gastaldo (Heidelberg), Sebastian Kempf (Karlsruhe), Marc Schumann (Freiburg)

Project Description

DELight is a new particle physics experiment that can only be realized through the confluence of all six projects. Each project plays a fundamental and unique role, where the project described in the following is responsible for **developing and constructing the superfluid helium cell and the cryogenic platform** of the experiment.

A number of specific requirements must be met for the cell itself and the cryogenic environment in which it is operated. The cell temperature should be well below the superfluid transition to maximize the superfluid component and minimize scattering with thermal excitations. The operating temperature should be below 20 mK. This requires cooling the cell with a dilution refrigerator with sufficient cooling power and space for the cell and a film burner that is required to evaporate the superfluid film creeping up the walls of the cell. It should also be possible to operate the cryostat remotely. Here, a commercial dry dilution refrigerator will be used as cryogenic platform and adapted to the specific needs of the project. The superfluid ^{4}He itself must be purified and, in particular, freed from ^{3}He impurities in order to not impede the mean free pass of the athermal quasiparticles generated in an event. For this purpose, a heat-flush purifier operating at low temperatures and a super leak will be developed and integrated into the cryogenic setup. A sensitive level sensor is also needed to monitor the helium level in the cell.

1 Starting Point

State of the art and preliminary work

The basic principles of a particle detector based on superfluid helium were already developed and tested in the 1990s within the HElium Roton Observation of Neutrinos (HERON) project, whose goal was to measure solar neutrinos [1]. It was also understood back then that such a detection method would have high potential for the search for LDM [2]. At that time, however, the focus of the cryogenic direct searches for dark matter was in the mass range of WIMPs, so a corresponding project has never been established. A large-scale solar neutrino detector has also never been built because the solar neutrino problem, which concerned a discrepancy between the flux of solar neutrinos predicted from the luminosity of the Sun and the flux observed, was solved by the discovery of adiabatic flavor conversions inside the Sun [3]. Nevertheless, the HERON project laid the foundation for a particle detector based on the unique properties of superfluid ^{4}He.

HERON prototype and detection scheme. As part of the HERON project, a $3\,\ell$ prototype superfluid ^{4}He detector was built and operated at about 35 mK [4]. This cell was constructed and instrumented in such a way that it was possible to demonstrate and investigate the detection scheme of such a detector. In particular, movable radioactive sources mounted on superconducting stepper motors [5] and sapphire and silicon wafers equipped with Ir-Au thin-film superconducting Transition Edge Sensors (TES) and germanium Neutron Transmutation Doped (NTD) sensors located just above the liquid level were used to study the generation and detection of the different signal components. In the HERON project the sources were low activity ^{241}Am for 3-5 MeV α-particles and ^{113}Sn for 364 keV electrons. X-rays from ^{55}Fe as well as from the ^{113}Sn and ^{241}Am sources were used for calibration.

When a particle stops in the superfluid, the initial energy loss is primarily by ionization which initiates a cascade of processes eventually terminating with the energy distributed among phonons and rotons (collectively referred to as quasiparticles), photons and a few long-lived excimers. How the energy is ultimately divided among these three channels depends on the density of primary ionization along the track. For example, a minimally ionizing electron loses 30 keV/mm, while a stopping α-particle loses 3×10^4 keV/mm. This difference results in a 3:1 ratio of UV radiation/keV in favor of the electron - quite different from other noble gas liquids. Conversely, the α-particle has a 4:1 advantage in quasiparticle emission [6].

When the quasiparticles are radiated from the particle track, they propagate ballistically at speeds typically of 150-200 m/s. Those which reach the free surface of the liquid and whose energy is greater than the binding energy of helium to itself can cause quantum evaporation. The latter is a process in which one phonon or roton can evaporate one helium atom and does so in about 30% of the cases [7] . Particularly for rotons, energy and momentum conservation at the evaporation surface place constraints on the range of incident roton angles which can cause evaporation [7]. The helium binding energy is 0.67 meV and the typical quasiparticle energies involved are $\geq$ 0.8 meV; thus for a particle recoil in the 50 keV range a very large population of atoms is involved in the resulting evaporation burst. The evaporated atoms are adsorbed to the wafer and their deposited binding energy produces a heat pulse in the detector.

The scintillation UV photons result from the radiative decay of helium singlet excimers formed along the track and have energies in the range of 14-20 eV but peaked at 16 eV. Since the first excited state of atomic helium is at 21 eV the liquid is transparent to these photons. The silicon and sapphire wafers are highly absorbent for photons at these energies and thus create a prompt heat pulse. The two contributions, photons and quasiparticles, can be distinguished by their relative times of arrival on the wafer [8]. In the HERON project the thresholds for energy transferred to the wafers was 300 eV so single photons were not detectable.

Along the track also triplet excimers are produced which have a remarkably long lifetime of about 13 s [9]. Decays of both singlet and triplet excimers have been detected with a TES detector emerged in superfluid helium radiated with gammas from a 100 µC ^{22}Na source located outside the cryostat [10]. The resolution of the TES detector was sufficient to resolve events from single excimers.

Helium purification and filling system. Ensuring ballistic propagation of quasiparticles throughout the entire liquid requires the purification from ^{3}He isotopic impurities since the quasiparticle scattering cross section for ^{3}He is $\sim 10^{14}$cm^2 and the natural concentration is $\sim 10^{-7}$. To reach the necessary mean free paths, the concentration must be reduced to below $\leq 10^{-9}$. Removal of ^{3}He via a heat-flush purifier to concentrations lower than 10^{-12} has been demonstrated [11]. Such a purifier is based on the interaction of the normalfluid component of superfluid ^{4}He with ^{3}He and can be integrated into the filling system. A superleak in series with the heat-flush purifier can be used if necessary and can act at the same time as thermally activated valve to control the filling. It should be pointed out that below 100 mK residual ^{3}He impurities will be preferentially located at the free surface of the superfluid ^{4}He, further reducing the concentration in the bulk of the liquid helium.

Keeping the above-liquid detectors film free. A very important aspect for the proper operation of the superfluid helium detector proposed here is that the above-liquid cryogenic wafer calorimeters must be kept free of a helium film, since a helium film significantly degrades the performance of such a wafer calorimeter in two ways: First, the film adds a large heat capacity, and second, the signal gain stemming from the binding energy difference when helium condenses on a bare silicon or sapphire wafer instead of on a helium film is completely reduced.

Since the detector is operated at a temperature well below 100 mK, where the gas density is of the order of $10^{-11}\,\mathrm{cm}^{-3}$, there are essentially no atoms in the gas phase above the liquid helium at this temperature and thus condensation on the detectors from the gas phase is irrelevant.

However, helium is forming films on surfaces even against gravity and in the superfluid state, these films will creep up walls and will wet the suspended above-liquid detectors. Various technologies have been demonstrated which can prevent or reduce film flow to the suspended wafers, including film burners as used in the HERON project [12], knife edge devices of atomic sharpness [13–15] and bare surfaces of non-wetable materials such as cesium and rubidium [16, 17]. Recently preventing helium film flow using cesium has been demonstrated in the context of a prototype superfluid helium detector for dark matter searches in the HeRALD project [18].

Level sensor. The suspension of the wafer calorimeters above the liquid level of the superfluid helium should have only a small gap to the liquid to enhance the efficiency of the quasiparticle detection. Therefore a precise level meter is needed to monitor the filling and adjust the gap. In the HERON project a pair of vertical coaxial cylindrical tubes inside the cell was used that formed a capacitor with helium as a dielectric. Despite the very tiny dielectric constant of liquid helium of $\epsilon_r \approx 1.075$ this device, read out be a standard capacitance bridge, allowed to measure the level with an accuracy of 500 µm [19].

Similar devices have also been developed and used in xenon dark matter experiments. In the XENON1T experiment, for example, two cylindrical level meters of 1360 mm length measure the liquid Xe level during filling and recovery, with 2 mm precision. In addition, parallel-plate capacitive level meters are installed to monitor possible tilts. They cover a dynamic range of 10 mm and have a precision of $\sim$ 30µm [20].

Cryogenic and detector platform. In the HERON project, a specially designed and self-constructed wet dilution refrigerator had been used as cryogenic platform [12]. One special feature was its ability to take out large amounts of heat at 200 mK and at 100 mK, while at the same time being able to maintain a relatively low base temperature at the mixing chamber. This was necessary because of the operation of the film burner. It was achieved by splitting the continuous heat exchanger mounted below the still in three parts and adding small copper boxes filled with sintered metal powder as thermal contact points in between. In this way about 500 µW could be removed from the condenser of the film burner at 200 mK by connecting it to the first box and to anchor the bottom of the filmburner at 100 mK. Below the continuous exchanger, two step heat exchangers, and finally the mixing chamber was mounted. The refrigerator was intended to operate at circulation rates up to 1 mmol/s. The temperatures given here are for a rate of 0.5 mmol/s. At this rate the wafer calorimeters reached 35 mK, which was at the time a limiting factor for their resolution. The wafer calorimeters used in the HERON project were suspended above the liquid. The detector platform consisted of a massive copper block hanging from a thin oxygen free high conductivity (OHFC) copper tube with an outer diameter of 2.54 mm and an inner diameter of 1 mm was used for thermally anchoring the detectors at the mixing chamber and feeding in the wiring for the detectors. The copper block was used to reduce vibrations. [19]

In the HeRALD project, a prototype cell with 100 mℓ superfluid helium has been operated in a dilution cryostat without film burner, but using Cs coating for preventing film flow to the calorimeters [18]. This cell was used to characterize several aspects of the detection scheme. The investigations largely confirmed the results of the HERON collaboration and expanded the knowledge about the UV photon spectrum and long-lived triplet excimers.

Preliminary work. C. Enss has been a member of the HERON collaboration and was involved in the development and construction of the 3 ℓ prototype superfluid He cell, the film burner and the detection system based on wafer calorimeters. He also participated in the early experiments proofing the concept of such a detector and investigating the different signal channels [7, 21]. Many key parameters were determined at this time. An important finding was the anisotropy of the quasiparticle signal that allows to obtain detailed information on position, energy, and track direction of particle events [8]. Recently it was suggested that such an anisotropy can be exploited even at very low recoil energies, if the quasiparticle signal can be measured with sufficient resolution by the in-liquid MMC wafer calorimeters [22]. In the initial phase of the HERON project the idea of MMCs was born and C. Enss conducted a first prove of principle experiment [23]. Later at Heidelberg he started a broad developing effort to realize and establish this technology.

In this context C. Enss, L. Gastaldo and S. Kempf have been working together since a long time and have extensive experience with cryogenic detectors, superconducting electronics and low-temperature physics. Together they have developed and used cryogenic detectors in many projects over the last two decades [24]. They have gained extensive experience in adapting cryogenic systems to integrate micro-calorimeters used for various applications in different environments, such as beamlines, storage rings and EBIT facilities [25–28].

M. Schumann is a leading expert in the field of DM detection with cryogenic noble-gas detectors. He led the overall design and construction of the XENON1T [20] and XENONnT [29] low-background liquid-xenon time projection chambers (TPC) and assembled the XENON100 TPC [30]. His input for the design and construction of the superfluid cell and the cryogenic environment will be crucial for achieving the goals of this project.

2 Objectives and work programme

2.1 Anticipated total duration of the project

The total duration of this project is fully aligned with the timeline of DELight phase-I as described in Sec. 2.2 of the “Overall Description of the Research Unit and the Coordination Proposal”. The anticipated total duration of the project is four years.

2.2 Objectives

One main objective of this project is the development, construction, commissioning and characterization of the superfluid helium cell including a film burner, a purification system, a level meter and a detector platform. A second main objective is the integration of this cell with all components in a suitable customized cryogenic platform. The latter will be adapted to a new commercial dry dilution refrigerator, that will be installed, commissioned and tested. A third main objective is R&D work in various directions in particular for up-scaling and technology improvements for the second phase of DELight. In addition, this project will be involved in the first science run of DELight.

Both the helium cell and the cryogenic platform are central parts of the DELight experiment and are interrelated with all other work packages. Design and construction of the cell has to be developed in close cooperation with P2 and P3. The cryogenic platform is designed, selected, facilitated and commissioned in collaboration with all other projects P2-6.

2.3 Work program including proposed research methods

The work program of this project consists of six work packages with 18 tasks. It is aimed at the realization of a superfluid helium cell integrated into a suitable cryogenic platform to be used as detector in DELight. Fig. 1.1 provides an overview of work packages related to this project. The work program assumes that the procurement of the cryostat is completed after 18 months, which is realistic given the 8 to 10 month delivery span stated in the quote. If, however, there are unexpected delays the work on the film burner, the cell and the R&D using the small cell can still proceed.

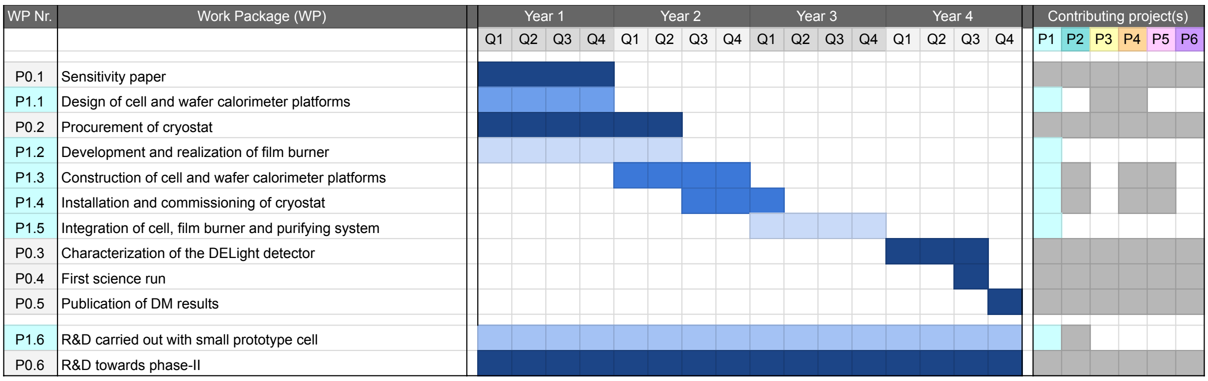

Figure 1.1: Summary of the P1 work programme. The work package (WP) numbers indicate the respective lead project (here P1) and the count within that project’s list of WPs. The P0 identifier is used for WPs that are equitably performed by all participants of the RU. The shades of blue within the timeline indicate the amount of contributing projects. The lightest blue is used for WPs only conducted within P1. The darkest blue is used for WPs to which all projects P1 - P6 contribute. The rightmost block of the program signals the lead project (color) and the further contributing projects (gray).

P1.1: Design of cell and wafer calorimeter platforms

The helium cell with all components including a film burner will be integrated in a commercial dry dilution refrigerator having two separate dilution units to be able to provide the necessary cooling power and to allow for cooling the cell and running the film burner independently.

Overall design and thermal anchoring of cell and film burner. The cell will be designed to contain about $10\,\ell$ of superfluid helium having three different sections connected by stainless steel flanges each equipped with a superfluid tight indium seal. The lower section will have a thick copper plate for thermalizing the superfluid helium. This plate will be thermally connected to one dilution unit of the dry dilution cryostat. This will allow to cool the liquid helium and the in-liquid wafer calorimeters down to below 10 mK. The bottom copper plate will also serves as basis to mount the in-liquid wafer calorimeters system and the level meter. It also contains all necessary superfluid-tight feedthroughs in the cell. The upper section with a top plate made out of stainless steal will contain the suspended wafer calorimeters system, the in and outlet of the helium and the connection to the film burner. The middle section will be a cylindrical tube made out of stainless steal connecting the top and bottom part. This construction allows for easy and independent access to the wafer calorimeters systems, above and in the liquid. A schematic of the overall design of cell and film burner is shown in Fig. 1.2.

Wafer calorimeter platforms for in-liquid and above-liquid detectors. The wafer calorimeters in the liquid will be mounted on a hexagonal or octagonal copper support structure, which will be optimized by finding the best compromise in minimizing the overall amount of cooper and having a sufficiently ridged structure with minimal vibrations. The wafer calorimeter itself will be attached to this frame so that as little mechanical stress as possible is imposed on them during the cool down, because stress induced excess events as seen in many other cryogenic detector systems [31] should be minimized. The design of the wafer holders and the support structure will be done in close collaboration with P2. First stage custom-made dc-SQUID amplifiers will be mounted on the same support structure in the vicinity of the wafer calorimeters and connected via wire bonding to the MMCs on the wafer. The wiring of the SQUIDs and the wafer calorimeters will by guided in superconducting shielded cable channels to the feedthroughs in the bottom plate of the cell.

The suspended wafer calorimeters above the liquid will be mounted on a wafer platform that is thermally anchored and mechanically connected to the mixing chamber through a copper tube through the film burner. As discussed in work package P1.2, the diameter of this tube determines the volume rate of film flow to the film burner and thus the power consumption of the film burner. This means the size of the circumference of the mechanical structure going through the film burner to the mixing chamber is limited by the available cooling power of the second dilution unit. A copper tube will be used for this mechanical structure that allows to thermally anchor the wafer platform and serves as a cable channel out of the cell. The top of this copper tube needs to have a superfluid-tight closing with feedthroughs for the SQUID and detector wires. The mounting platform itself will be a copper structure that allows for a close packing of the wafer detectors together with the SQUIDs. It will be optimized for low vibrations, for minimizing stress and material.

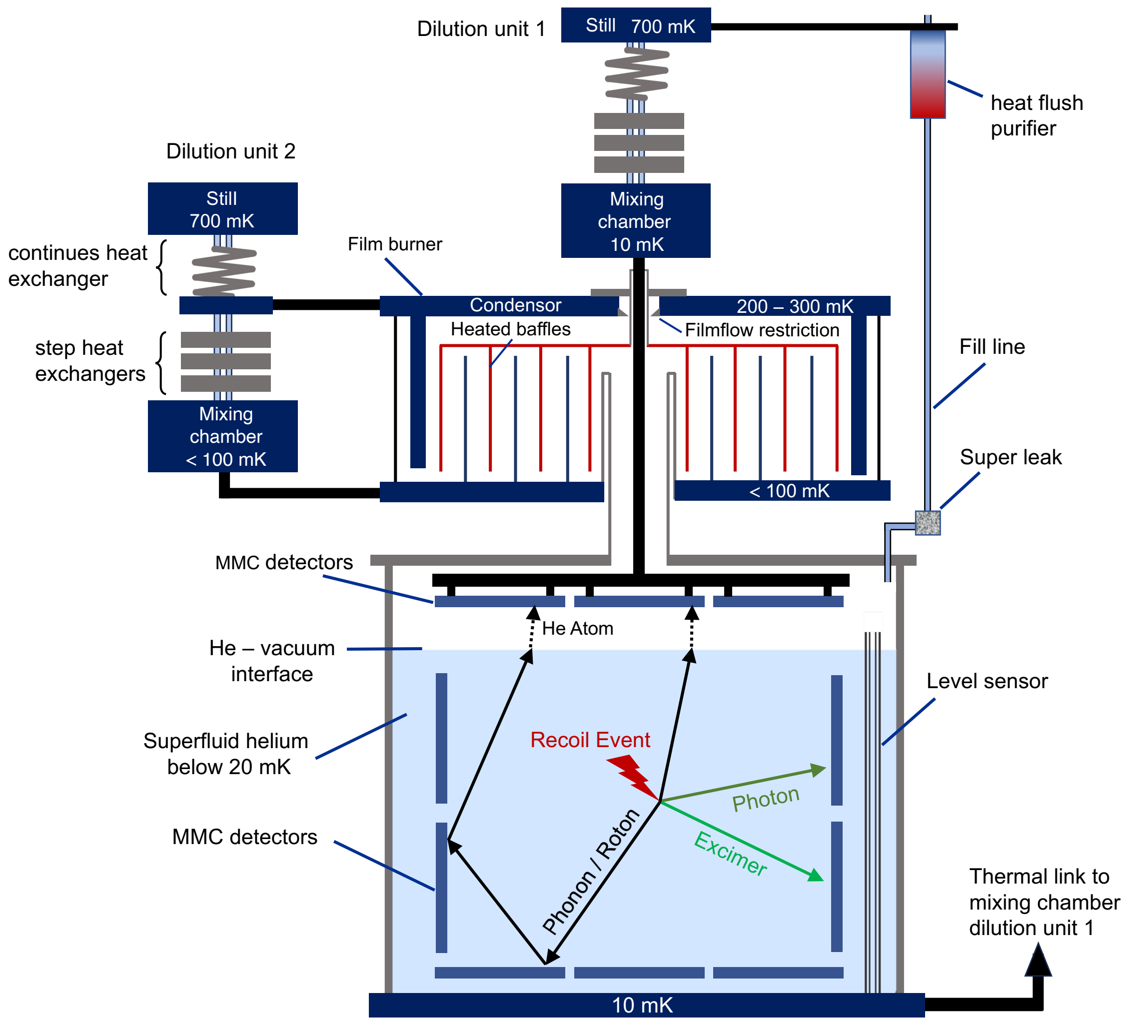

Figure 1.2: Schematic representation of a superfluid helium cell with film burner, heat flush purifier, level sensor and MMC-based wafer calorimeter system. In addition the principle detection channels (phonons/rotons, photons and excimers) are depicted.

Filling, purifying and exhaust system. Because helium is the only element which remains a liquid at temperatures close to 0 K, all other elements freeze out on the walls of the container of the liquid or structures within it. The only impurity which can exist in superfluid ^{4}He are ^{3}He atoms. As mentioned above the ^{3}He concentration has to be reduced by several orders of magnitude to not limit the mean free path of quasiparticle by ^{3}He-scattering.

This will be achieved by using a heat flush purifier, which is a tube-like device in line with the filling capillary. A heater at the end of the tube closest to the cell produces a "wind" of normal fluid excitations which sweeps all the ^{3}He away from the heater due to the very large scattering cross-section between the excitations and the ^{3}He atoms. The heat is removed from the cooler end of the heat flush tube which is thermally anchored to the still of the dilution refrigerator. The purified superfluid travels toward the heater, and if the net mass flow of fluid is towards to the heater, only this pure superfluid component passes through the flushing tube. The effectiveness of this process in purifying the helium depends upon the whether the ^{3}He is able to diffuse back against the stream of normal fluid.

A flow rate of approximately 3 mmol/s will be used to be able to fill the cell with 8 ℓ in a day.

The superfluid velocity should be much less than the critical velocity for helium flow. On reaching the critical velocity there will be a large viscous resistance to fluid flow causing the fluid to heat up, and the flow will become turbulent as vortices are created. To reach that condition for a volume rate of 3 mmol/s, the power into the heat flush device needs to be above 3 mW.

The purifying system needs two more components to function. One is a superleak made of fine compressed powder in a stainless steel tube, which is in the fill line below the heat flush purifier. Its main function is to be operated as thermally-activated value to precisely control the filling. When the desired level is reached the superleak is heated above the lambda point and the superfluid flow stops. At the same time it is used to block residual ^{3}He after the purifier. After the filling is stopped, a needle value above the still in line the fill capillary is closed and the concentrated ^{3}He at the cold end of the heat flush device can be pumped away.

For emptying the cell before warming up a second capillary is installed at the top of the cell, as well as a burst disc in case of a sudden quench of the cell. In order to further reduce any remaining ^{3}He concentration in the bulk of the liquid a sinter with large internal surface will be mounted at inside the top of the cell. ^{3}He will first occupy all available state at the free surface and form a monoatomic layer.

Level meter and tilt sensors For measuring the level height of the liquid during filling and emptying of the cell a capacitive level sensor will be designed and contracted. Here we will use a scheme in which a coaxial cylindrical capacitor is part of a tank circuit, whose resonance frequency is used to monitor the level height. To monitor possible tilts, planar capacitors with fingers will be developed that will have a dynamic range of 10 mm and a precision better than 100 µm. Four of these senors will be used and placed just below the above-liquid detectors on the inner wall of the cell.

Thermometry for cell. The bottom copper base plate of the cell will be equipped with a custom-made current noise thermometer for calibration and a magnetic susceptibility thermometer for temperature regulation. Additional susceptibility thermometers will be used to monitor and regulate the temperature of the suspension system of the above liquid detectors.

P1.2: Development and realization of film burner

For preventing film flow to the above liquid wafer calorimeters, a film burner will be designed and realized. In saturated vapor pressure a helium film formed on the all parts in a container above the liquid level whose thickness is given at height h about the liquid level by $g = (\alpha/gh)^{1/3}$, where g is the standard acceleration of gravity, α the Hamaker constant, the magnitude of which is determined by the dielectric properties of the wall and the helium. For $h = 10$ cm one finds a thinkness of about 200 Å. In the superfluid state these films can move without friction at the critical velocity, which is around 100 cm/s. As the depicted in Fig. 1.2, the film burner will consist of an evaporation and condensing platform.

Evaporation and condensing platforms. The film burner operates by heating a region in the path of the helium film flow to a temperature above which it evaporates. In this design the superfluid film flowing from the helium bath is prevented from reaching the detectors by intercepting the flow with a surface (indicated in red in Fig. 1.2) which is heated above 600 mK, causing the film to evaporate. The helium flow onto this surface is limited by a constriction in the support structure. If the vertical path at the top of the device has a perimeter of 1.8 cm it limits the volume flow rate to $2.5 \times 10^{-4}\,\mathrm{cm}^3/\mathrm{s}$ which requires approximately 1.5 mW to evaporate. The majority of the helium atoms are recondensed onto a copper plate immediately above and to the sides of the evaporator. The condenser is connected by copper posts to the 200 mK stage of the dilution unit for the film burner to remove the condensation energy. This energy is again typically about 1.5 mW but varies slightly because the helium film thickness varies slightly according to the level in the cell. Below the evaporator a set of concentric baffles (grey) shield the film-free region from the evaporated helium atoms. The condensing platform will be equipped with a copper sinter film to enhance the surface and thus the sticking probability.

Thermal insulation from mixing chamber. The design of the film burner requires a careful consideration of heat sinking and thermal insulation because of very different temperatures will be present in close vicinity. The main focus will be on the keeping the dilution unit for cooling the detectors and the helium in the cell as independent of the film burner operation as possible. A critical point will be here the top seal where the thermal connection to the mixing chamber of the dilution unit for cooling the detectors is fed through. Thin walled stainless steel tubes of appropriate length will be needed to provide sufficient thermal insulation. The overall thermal design is sufficiently complex that a full model simulation of all components is needed to aid the design.

Mechanical support and wiring scheme. Another aspect is the mechanical support of the film burner which requires careful considerations. Copper posts to different temperatures stages of the dilution unit for the film burner are needed, while the film burner structure itself will also be attached to the mixing chamber of the dilution unit that cools cell and detectors. Depending on the design of the cryostat and it two dilution units a well adapted mechanical support structure to film burner needs to be designed and constructed. In addition, the wiring scheme for the heaters and thermometers in the film burner including the appropriate feedthroughs has to be developed and realized.

P1.3: Construction of cell and wafer calorimeter platforms

Within this work package the detailed construction plans will be worked out for both the cell and the wafer platform. The parts will be made and assembled in the mechanical workshop at the Kirchhoff-Institute for Physics. After assembling, all feedthroughs are attached and room temperature leak testing takes place.

P1.4: Installation and commissioning of cryostat

This work package will deal with all aspects of the installation and commissioning of the dry dilution refrigerator used for DELight. The cryostat will have two dilution units and three pulse-tubes for pre-cooling.

Minimizing vibrations. The cryogenic MMC-based wafer calorimeters used in the experiment are susceptible to vibrations and their energy resolution and threshold can be impeded by exceeding a certain level of vibrations. Therefore, minimizing vibrations is an important aspect of installing the cryostat. Here we plan to isolate the compressors of the pulse tubes from the cryostat by using long tubes and locate the compressors in a separate room. In addition, damping material will be wrapped around these tubes. The rotary valves of the pulse tubes are separated from the cryostat and mounted on a stand-alone support. The tubing connecting pulse tubes and rotary valves will be wrapped with damping material. The effect of these measures will be monitored via accelerometer sensors and if necessary additional action will be taken.

Minimizing electrical and magnetic interference. Electrical disturbances can impact the performance of the wafer calorimeters severely. To reduce the influence of high-frequency electromagnetic perturbations low-pass filters will be installed for the critical cabling going into the cryostat. This techniques is used successfully for every cryostat by the low temperature group at Heidelberg University lead by C. Enss. In addition, a combination of μ-metal and superconducting shielding will be used to reduce the magnetic field effects.

Installing noise thermometers on both mixing chambers. In the process of commissioning the cryostat, a current noise thermometer at the mixing chamber of each dilution unit will be installed. These thermometers have been developed in the low temperature group at Heidelberg University.

P1.5: Integration of cell, film burner and purifying system

When all components are ready, the process of integration into the cryostat will be started. After mounting all mechanical components and making superfluid-tight joints to the cell the wiring of the detectors, the thermometers, heaters and readout will be inserted. For the second-stage SQUID amplifiers, housings with superconducting and μ-metal shields will be installed. After all components have been assembled in the cryostat, leak testing and checking of the wiring will be conducted. If everything works a first characterization run will take place during which the temperature distribution of cell film burner and filling system is tested as well as the heating systems. After passing this characterization, the cell will be filled the first time, testing also the purifying system and level sensors. A further step will be a test and characterization of the film burner operation.

P1.6: R&D carried out with small prototype cell

Within the work package an R&D program will be conducted for technology that can be used in a second phase of DELight. It also includes tests of technology and components that will be used in the first phase. For that purpose two small cells without film burner are constructed at the beginning of the project. One for tests of the new in-liquid detectors that will be operated at KIT and one for R&D regarding the detection scheme and several new technology components. The latter cell will be equipped with a purification system in order to do a test on this technology and to allow for investigating the scattering processes in superfluid helium without ^{3}He. The two cells will be constructed at the beginning of the project so that this R&D program can start right away and has not to wait until the main cryostat for DELight will be delivered.

Construction of two small cells for testing and R&D. Two cell of identical size and design will be constructed, both having a capacitive level sensor and feedthroughs for two detectors, heaters and superconducting motors. One of the cells will have in addition a purification system consisting of a heat flush purifier and a superleak. These cells will be constructed and assembled at the Kirchhoff-Institute for Physics. They will be tested at room temperatures and low temperatures. The system without purifier will go to KIT and will be used in P3 in the context of detector development.

Test for filling, purification exhaust system. All components of the filling, purification and exhaust system will be tested in detail to learn whether these systems are working or adjustments need to made. Based on these results the filling, purification and exhaust system for the large cell will be designed and constructed.

Search for quasiparticle signals in liquid. An important early investigation will be a systematic search for a quasiparticle signal with in-liquid wafer calorimeters. Such signals have not been considered before, but could potentially enhance the sensitivity of a dark matter search greatly. The in-liquid wafer calorimeters work on the basis that the thermal boundary resistance (Kapitza resistance) is very large at very low temperatures between any solid material and liquid helium. This isolated the wafer calorimeters from the helium and the UV photons can be detected without degradation by the heat capacity of the liquid. However, high frequency quasiparticles as they are produced in nuclear and electron recoil events have shown to have a much reduced Kapitza resistance as demonstrated in thermal conductivity experiments at higher temperatures and with rough surfaces [32]. We plan to do experiments with MMCs having roughened silicon wafers as absorbers and heater in the liquid in the small test cell to see whether such signal can be observed and what the sensitivity limit is. To investigate a possible enhancement of the transmission of quasiparticles into the absorber, we also will study wafer absorbers with different superconducting layers on the surface to act as converters by breaking Cooper pairs and transmitting low frequency phonons into the silicon.

Test of superconducting motor. To calibrate the detector system in the large cell movable heaters and radioactive sources are needed. We will use small commercially available stepper motors, which we will modify by replacing the normal conducting coils by superconducting coils. These motors will be tested in the small cell.

Investigation of prompt UV-photons and delayed triplet excimers signals. Signals from the decay of singlet excimers and triplet excimers have been observed before. The task here is to detect these signals with the new MMC in-liquid detectors and characterize their response.

R&D on a quasiparticle reflection system. In the both the HERON [33, 34] and the HeRALD project [18] the reflection coefficient for quasiparticles has been determined to be around 30% independent of the materials and surface conditions. This independence is somewhat surprising but might be explained by adsorbates resulting from ambient conditions when the experiment was sealed and cooled down. We will conduct experiments in the small cell with in-situ freshly cleaved crystals to investigate this important parameter. One possible realization of such an experiment is a graphite crystal that is exfoliated within the cell using a superconducting motor.

R&D on new flow reduction or prevention systems. Later stages of DELight will require much larger amounts of liquid helium and many more wafer calorimeters. For the suspended above-liquid wafer calorimeters this means that many more leads have to be channeled through the film flow restriction. To achieve that the film flow restriction has to be widened, which increases the volume rate of film flow to the film burner and in turn the heat load on the second dilution unit, potentially overloading it. To reduce the film flow we will do R&D on knife-edge film flow restriction. These devices work by introducing atomically sharp edges into the film flow path, whose small and radius of curvature give rise to a large surface tension energy and in turn thins the He film. It has been demonstrated that the film flow can be reduced by 30% using knife-edge devices made from anisotropically etched silicon with KOH [13–15]. One of such knife-edge devices that are used in the cryogenic exhaust system on the x-ray satellite XRSIM is seen in Fig. 1.3 (from [35]).

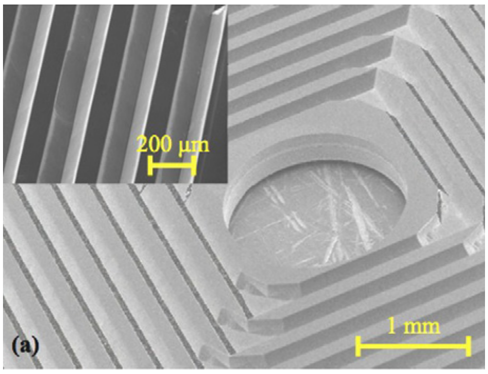

Figure 1.3: SEM image of a film-flow restriction device with 10 knife-edges in series as used in XRSIM.

These knife-edges have edges with corner's radius of curvature in the order of 10 nm and thus are far from being atomically sharp. Here we will develop new double-layer knife-edges were a ultra-thin film of silicon-nitride on silicon is prepared free standing and will be etched through creating a sharp overhanging knife-edge. Recently the growth of ultra-thin Si_3N_4 films on Si(111) was demonstrated with thicknesses between of 5 nm and 7 nm. An possible alternative is graphene overhanging a hole on a suitable substrate. Successful wafer-scale transfer of graphene onto different substrates with strong bonding has been reported recently [36].

A separate path to a possible solution is to deposit a bare Cs film onto an inert substrate to block or reduce the film flow. This technique sounds easy at first, but has several technical challenges. Because Cs is highly reactive, the film has to be evaporated after the cell is closed a low temperatures. The substrate has to be inert to eliminate chemical reactions with the substrate material. The film evaporates partly after warming up the cryostat potentially contaminating the cell and the detectors. The inert substrate has to be refreshed before every new cool-down, which means to dissemble the complete detector system each time. In addition, it has not been shown that this technique can be used reliably.

P0.1-6: Procurement of cryostat, detector characterization, first science data, DELight publications, R&D towards phase-II

The work packages P0.1-6 have no leading project but are equitably performed by all participants of the RU. They are an expression of collaboration within the entire RU and thrive on the strong synergies between the projects. The activities of the RU during phase-I of DELight are framed by two main publications, a sensitivity paper (P0.1) at the beginning of the funding period and the publication of the first science results (P0.5) at the end of the funding period. These publications require input from all projects and expertise from all members of the RU and will help shape the science output of DELight. Several additional publications are planned to be published within the funding period. The cryostat is part of the coordination project and its procurement (P0.2) will be carried out by the RU together, just like the characterization of the whole DELight detector (P0.3) and the DELight operations and monitoring of the data taking during the first science run (P0.4). In parallel to phase-I, the RU will jointly start R&D towards phase-II (P0.6). A few key contributions of P1 will be highlighted in the following.

The R&D of P1 will include work on a quasi-particle reflection system and a new film-flow reduction or prevention system as well as calorimeter development to increase the sensitivity of the in-liquid detectors for quasiparticles. This part of the calorimeter development is done by using the small He cell at the Kirchhoff Institut for Physics because it will be equipped with a purifying system.

2.4 Handling of research data

The same text applies as in Sec. 2.3 of the "Overall Description of the Research Unit and the Coordination Proposal".

2.5 Relevance of sex, gender and/or diversity

Sex and/or gender is not relevant to the research project. Though we strive for a diverse group of researchers, the level of diversity is also not relevant to the research project.

3 Project- and subject-related list of publications

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4 Supplementary information on the research context

4.1 Ethical and/or legal aspects of the project

4.1.1 General ethical aspects

We do not anticipate any risks and/or harm to individuals or groups or the environment and/or the potential for other negative effects that might be posed by our research.

4.2 Employment status information

Last name: Enss
First name: Christian
Employment status: Full professor (C4) at Heidelberg University

Table 1.1: Individuals who will work on the project but will not be paid out of the project funds.

Name and academic title	Employment status	Institution	Type of funding
Paid by institution			
Dr. Andreas Fleischmann	Staff scientist	UHD	institutional
Dr. Andreas Reiser	Staff scientist	UHD	institutional
Priv. Doz. Loredana Gastaldo	Staff scientist	UHD	institutional
Prof. Dr. Christian Enss	Full professor (C4)	UHD	institutional
Prof. Dr. Marc Schumann	Full professor (W3)	UFR	institutional
Prof. Dr. Sebastian Kempf	Full professor (W3)	KIT	institutional

4.3 First-time proposal data – Does not apply.

4.4 Composition of the project group

A. Fleischmann, L. Gastaldo, S. Kempf and C. Enss are leading experts in the field of cryogenic detector development, realization and application, including the integration of large detector systems into custom-designed cryogenic platforms. A. Fleischmann, A. Reiser and C. Enss have extensive experience in the development of cryogenic systems, including setting up experiments with superfluid helium. M. Schumann is a leading expert in the field of DM detection with cryogenic noble-gas detectors.

4.5 Researchers in Germany with whom you have agreed to cooperate on this project – Does not apply.

4.6 Researchers abroad with whom you have agreed to cooperate on this project – Does not apply.

4.7 Researchers with whom you have collaborated scientifically within the past three years

All respective researchers are included in Sec. 5.7 of the overall description.

4.8 Project-relevant cooperation with commercial enterprises – Does not apply.

4.9 Project-relevant participation in commercial enterprises – Does not apply.

4.10 Scientific equipment

Several large-scale devices and facilities are available for this project. To operate the small cell and to perform most of the R&D program of this project, a dry dilution refrigerator with a power of 0.3 mW at 100 mK can be used in part time. It allows the installation of a purification system.

In addition, the clean room facility of the Kirchhoff-Institute of Physics can be used to carry out the development of knife-edge devices and micro-fabricated tilt sensors. It will also be used to micro-fabricate the SQUIDs for the noise thermometers for the cell and the DELight cryostat, as well as the MMCs for initial measurements in the small cell. The clean room includes, among other things, several UHV sputtering systems, a mask-less direct-writing laser lithograph, several plasma etching systems.

4.11 Other submissions – Does not apply.

4.12 Other information – Does not apply.

5 Requested modules/funds

5.1 Basic Module

5.1.1 Funding for Staff

The following staff is requested for the successful completion of this project within DELight:

- **1 Postdoctoral Researcher for 4 yrs:** This postdoc will be developing and constructing the main cell including film burner, purification system and the detector platform. In addition, the postdoc will be installing the cryostat, integrating all components and carrying out the necessary tests. The postdoc will also oversee the construction of the two small cells and its components and the R&D program carried out with the small cell at Heidelberg.
  We expect annual costs of 80,100 €/year for the 100% TV-L E13 position, summing up to **320,400 €** in total.
- **1 Doctoral Researcher for 4 yrs:** The doctoral researcher will be constructing the two small cells, including level sensor and purification system and will carry out the R&D program for seen for the small cell at Heidelberg.
  We expect annual costs of 55,575 €/year for the 75% TV-L E13 position, summing up to **222,300 €** in total.

5.1.2 Direct Project Costs

5.1.2.1 Equipment up to € 10,000, Software and Consumables

The total cost for equipment, software and consumables is estimated to be **32,000 €** for the full funding period. The following table summarizes the breakdown of the cost. More detailed information is given afterwards.
Item 1: For the planned experiments in the small cell and the R&D towards the second phase of the project specially designed MMC detectors are necessary that will be developed and fabricated in the clean room of the Kirchhoff-Institute for Physics. In addition, research and development work for suitable knife edge film flow restrictions are conducted at this clean room facility. The works require a number of consumables. They include Si and sapphire substrates, chemicals (photo resists, developers, solvents, substrate detergents), process gases for material deposition and etching, deposition materials, printed circuit boards as well as general consumables such as gloves, glassware, cleaners.

Table 1.2: Costs for equipment, software and consumables.

Item	Description	Cost [EUR] incl. VAT
1	Cleanroom consumables	15,000
2	μ-metal shielding and superconducting shielding	8,000
3	Capillaries and tubing	2,000
4	Superfluid-tight feedthroughs	6,000
5	4 Superconducting motors	1,000
	Total	**32,000**

Item 2: The 1st and 2nd stage SQUIDs as well as the MMC-based wafer calorimeters need a reduced and stable magnetic field environment. Therefore μ-metal and superconducting shielding of several components are needed. In particular, a global μ-metal and superconducting shield for the cell and its components is needed.

Item 3: For construction of the film burner, the cell and the purification system thin walled stainless steel tubing and capillaries are necessary.

Item 4: Both the in-liquid and the above-liquid wafer calorimeters have to be wired into the cell through superfluid tight multi-pol connectors. Here commercially available glass sealed connectors are foreseen.

Item 5: Finally for the calibration of the detectors in the main cell and for the experiments carried out in the small R&D cells superconducting stepper motors are necessary to move radioactive sources and heaters. The fund are obtaining the parts of stepper motors which normal coils that can be rewired with superconducting leads.

5.1.2.2 Travel Expenses

For DELight Project 1 a total of **17,400 €** travels funds are required to cover the following costs:

- **International conferences.** The attendance of and contribution to relevant international conferences such as the International Workshop on Low-Temperature Detectors (LTD), the International Symposium on Quantum Fluids and Solids (QFS) or the International Conference on Low Temperature Physics (LT) provides important visibility, networking, and interpersonal communication opportunities strengthening DELight and the careers of its scientists. We estimate the cost for a typical 5 day long international conference or workshop to be 3,000 € and foresee one international conference for each person funded by this RU as well as the applicant. The total amount required is thus **12,000 €**.

- **DPG Spring Meetings.** Doctoral and postdoctoral researchers, as well as the DELight project which they represent, strongly benefit from attending the annual Spring Meeting of the DPG

(German Physical Society) every year. Especially doctoral researchers use this opportunity for their first presentations to the wider scientific community. We estimate the costs for a 5 day long trip to the DPG Spring Meeting at a German city at 1000 € and plan with six trips during the funding period, which amounts to **6,000 €**.

- **DELight in-person meetings.** This project is tightly connected to other DELight projects (e.g., P1 – cryogenic setup and ^{4}He cell, P2 – MMC detectors, P3 – Low-background environment and P5 – Data acquisition and computing), which requires close coordination with our colleagues. This requires occasional travel to the other institutions for day-long in-person meetings. Here we can clearly benefit from the close geographical proximity of the three DELight institutions. We estimate the average costs for a short trip at 150 € and anticipate four short trips per year. This amounts to **2,400 €** in total. (The costs for traveling to or hosting the two in-person collaboration meetings per year are covered by the Coordination Project.)

5.1.2.3 Visiting Researchers (excluding Mercator Fellows) – Does not apply.

5.1.2.4 Other Costs – Does not apply.

5.1.2.5 Project-related Publication Expenses

Does not apply. Project-related publications will be published in journals of the Sponsoring Consortium for Open Access Publishing in Particle Physics (SCOAP^3) where no extra costs occur. In addition, all articles will be posted on the open-access arXiv preprint server.

5.1.3 Instrumentation

5.1.3.1 Equipment exceeding € 10,000

For successful completion of DELight Project 1, resources for equipment exceeding € 10,000 are required. The total cost is estimated to be **41,843 €**. Table 1.3 summarizes the breakdown of the cost. More detailed information are given in the item description afterwards.

Table 1.3: Costs for equipment, software and consumables.

Item	Description	Cost [EUR] incl. VAT
1	One three-channel high-speed FLL SQUID electronics	29,348
2	16-bit ADC with 16 channels	12,495
	Total	**41,843**

Item 1: For the R&D program conducted in the small cell a SQUID electronics is need to readout several MMCs. In addition, the main cell and the film burner will be equipped with in-house custom-made noise thermometers. For their readout 2 SQUID readout-channels are needed.
Item 2: A 16-bit ADC is need for reading out the signals of the MMCs in the small cell.

5.1.3.2 Major Instrumentation exceeding € 50,000 – Does not apply.

P2 – MMC-based detection system

Applicant: Sebastian Kempf (Karlsruhe)
Co-applicants: Christian Enss (Heidelberg), Belina von Krosigk (Heidelberg)

Project Description

DELight is a new particle physics experiment that can only be realized through the confluence of all six projects. Each project plays a fundamental and unique role, where the project described in the following is responsible for the **magnetic microcalorimeter (MMC) based detection system** that is used for measuring the different signals that are created by interaction between a DM particle and a ^{4}He atom within the superfluid ^{4}He target.

The DELight detector will consist of energy- and time-resolving wafer calorimeters, some of which will be located above the liquid, while others will be immersed in the superfluid. The calorimeters above the liquid will measure the energy deposited by ^{4}He atoms evaporating from the liquid as well as emitted photons propagating in direction towards the liquid-vacuum interface. The calorimeters within the liquid will ideally cover the entire cell surface and sense triplet excimer states and scintillation photons emitted in direction towards the in-liquid vessel walls. For both sites, the calorimeters must be compatible with mK temperatures, must provide an excellent energy resolution to achieve a low energy threshold as well as to discriminate different photons and must give timing information to distinguish prompt and delayed excitations. For this reason, the wafer calorimeters within DELight will be based on magnetic microcalorimeters (MMCs).

In the first phase (phase-I), the DELight detector will consist of about fifty MMC-based wafer calorimeters. One fifth of them will be placed above the liquid, the others will be immersed in the superfluid. The energy resolution of the calorimeters will be in the range of 5-6 eV, corresponding to a threshold of 20 eV. In the second phase (phase-II), the DELight detector will be upgraded to approach full surface coverage of the entire cell. Moreover, we will add next-generation calorimeters with 1-2 eV energy resolution to be developed to yield a threshold of 5-10 eV.

1 Starting Point

State of the art and preliminary work

DELight relies on measuring the recoil energy that is released during the interaction of a DM particle and a ^{4}He atom within the superfluid ^{4}He target. This energy is partitioned among prompt IR und UV scintillation photons, triplet helium excimers as well as quasiparticles (phonons, rotons), the latter ejecting a burst of ^{4}He atoms when reaching the free surface of the liquid. These unique signal channels can be observed and distinguished by a cutting-edge energy- and time-resolving detector comprising wafer calorimeters that are located both above and within the liquid. Combining independent calorimeter signals not only allows to discriminate between dark matter recoils and backgrounds, but also to differentiate between recoil events with high and low energy. The exceptionally low energy of quasiparticles allows potentially for an extremely low energy threshold, only limited by the capability of the wafer calorimeters.

Singlet helium excimers decay instantly after generation via UV photon emission and cause a prompt detector signal. Quasiparticles propagate ballistically at a speed of $\mathcal{O}$(150-200 m/s) through the liquid and eventually reach the surface of the liquid. The resulting burst of ^{4}He atoms leads to a temporally broad energy deposition in the detector that is delayed by the quasiparticle propagation time with respect to the UV photons. Triplet excimers have a lifetime of about 13 s and propagate as ballistic molecules at a speed of $\mathcal{O}$(1 m/s) through the superfluid. Some of them eventually decay or quench at a wafer calorimeter surface, causing an eV-range energy release that is delayed as compared to the quasiparticle and singlet excimer signal. Others might hit the walls or other parts of helium cell. Overall, the DELight detector must provide an energy resolution $\mathcal{O}$(1-10 eV) to sense UV photons and the burst of ^{4}He atoms as well as a time-resolution $\mathcal{O}$(1-10 µs) to distinguish the different signal channels by their time pattern. Nevertheless, the sensitivity of DELight improves greatly with even better energy and time-resolution. Sub-eV energy resolution, for example, will not only enable to detect IR photons, too, but also to sense ^{4}He bursts containing only a few evaporated helium atoms. Similarly, improving the time resolution further will allow for precise reconstruction of the event position as well as resolving directional information.

Cryogenic microcalorimeters. Calorimeter operation within and above the superfluid as well as the challenging requirements on energy and time resolution necessitates the usage of cryogenic microcalorimeters such as superconducting Transition Edge Sensors (TESs) [1] or Magnetic MicroCalorimeters (MMCs) [2, 3]. These are thermal detectors that evolved as key technology for various applications. They nowadays allow for groundbreaking experiments and will be essential for realizing superfluod helium-based dark matter experiments like HeRALD or DELight. Both, TESs and MMCs, rely on converting an energy input into heat by using a suitable particle absorber into which the energy is deposited. The resulting increase of detector temperature is monitored using an ultra-sensitive thermometer based on either the temperature-dependent resistance of a superconductor biased within its transition (TESs) or the temperature-dependent magnetization of a paramagnetic situated in a weak magnetic field (MMCs). For thermometer readout, superconducting quantum interference devices (SQUIDs) are used. They both provide an excellent energy and time resolution [4, 5], with MMCs achieving an world-leading energy resolution of $\Delta E_{\mathrm{FWHM}} = 1.25\,\mathrm{eV}$ for 5.9 keV photons [4].

Both, TESs and MMCs, have several advantages and drawbacks that relate to different aspects of a detector system. A statement which detector technology is suited best for a particular experiment is hence hard, if not impossible, as both detector types can be adapted in principle for many application. This is shown, for example, in that the competitor experiment HeRALD uses TESs and already achieved impressive results [6]. Nevertheless, DELight will comprise MMCs due to existing strong expertise within the group of applicants and the facilities available at both KIT and Heidelberg University. Overall, we expect that the HeRALD and DELight detector will show a similar performance but are subject to very different systematic effects affecting, for example, energy calibration, magnetic field susceptibility or long-term stability.

Phonon-mediated particle detection. The most simple picture of a cryogenic microcalorimeter assumes that an energy deposition E causes an increase of absorber temperature that is sensed by the thermometer. The temperature rise $\delta T = E/C_{\mathrm{tot}}$ is then simply determined by the total heat capacity of the detector C_{tot}. This simple picture, however, neglects the absorption and energy-downconversion processes within the absorber. For DELight, the absorber will be formed by a thin, large-area silicon or sapphire wafer. Energy deposition will then cause the creation of electron-hole pairs (if the energy is sufficient) as well as non-equilibrium, i.e. athermal, phonons. The latter can be sensed in either *thermal* or *athermal* mode. In thermal mode, the thermometer senses the equilibrium temperature of the calorimeter. Generated phonons must hence down-convert by anharmonic decay and isotope / mass defect phonon scattering until they eventually reach a thermal equilibrium state, characterized by a lattice temperature that is higher than before energy deposition. In this scenario, the temperature rise is given by $\delta T = E/C_{\text{tot}}$. In cold and pure dielectric crystals, however, the number of thermal phonons is very low and isotope / defect scattering rarely occurs. Athermal phonons hence exist for a long time and propagate ballistically through the crystal. This slows down the detector response as it takes several milliseconds until an equilibrium state is reached. In athermal mode, generated phonons are directly sensed via phonon collectors that connect to the thermometer. As a result, the signal rise time is not given by the time for reaching thermal equilibrium, but by phonon collection and temperature sensor thermalization. For MMCs, the latter can be as fast as 100 ns [3].

Phonon collectors can be either normal or superconducting. In the former case, the energy relaxation of phonons hitting the collectors is sped up due to the existence of conduction electrons and the resulting phonon-electron scattering. The deposited energy is then distributed in the electron system, the temperature of which is measured by the thermometer. For MMCs, the electron-spin interaction is very strong, even at low temperatures [2], and allows sensing any change of conduction electron temperature with a time constant less than 100 ns. The effective detector rise time is thus given by the phonon collection time and not the time until the calorimeter reaches thermal equilibrium. Nevertheless, the existence of conduction electrons entails a large heat capacity of the phonon collectors that can even dominate the total heat capacity of the calorimeter. A recent advancement of the LUMINEU light detector [7], for example, uses a 330 µm thick Si absorber and comb-shaped Au structures for phonon collection. Though the latter occupy only 0.7 % of the total absorber area, the heat capacity of the phonon collectors at the operation temperature is about 15 % larger than the absorber heat capacity.

Superconducting phonon collectors rely on Cooper pair breaking: When high-energetic athermal phonons hit the phonon collector, they break Cooper pairs, thus generating quasiparticles that energetically relax towards the gap edge via phonon release. The latter either breaks additional quasiparticles (if their energy is above the gap edge) or escape into the substrate. Assuming that the collector geometry is arranged such that quasiparticles can diffuse into a normal conducting material before recombination, electron-electron interactions become dominant and the energy is rapidly thermalized within the electron system. Again, the thermometer senses the resulting temperature rise of the electron system. As the electron-electron and electron-spin interactions are much stronger at mK temperatures than the electron-phonon interaction, the thermometer senses a rise of conduction electron temperature even before before the absorber reaches thermal equilibrium.

Direct-current superconducting quantum interference devices (dc-SQUIDs). Single-channel MMCs or small-scale MMC arrays typically comprise two-stage dc-SQUIDs operated with a direct-coupled high-speed SQUID electronics with flux-locked loop (FLL) feedback [8] for sensing the temperature-induced magnetic flux change of the paramagnetic temperature sensor. This results from the very large bandwidth, near-quantum limited noise performance as well as compatibility with operation temperatures well below 1 K of such SQUID setups. Two-stage dc-SQUIDs consists of a first-stage SQUID, to which the actual calorimeter is connected. It senses the magnetic flux change caused by the paramagnetic temperature sensor upon a rise of detector temperature. As the typical noise level of a first-stage SQUID is more than an order of magnitude better than the input noise level of even the best semiconductor amplifiers, an *N*-SQUID series array is used as low-noise amplifier to boost the output signal of the first-stage SQUID. Due to its large flux-to-voltage transfer coefficient, the SQUID array can be directly connected to the preamplifer of the FLL electronics providing flux feedback to the first-stage SQUID.

For achieving the best energy resolution, the input coil of the first-stage SQUID must be impedance-matched to the pickup coil of the attached MMC. Moreover, the Joule power dissipation of the first-stage SQUID must be minimized as it is placed in close vicinity to the calorimeter and potentially heats the temperature sensor above the heat bath temperature, thus impacting the energy resolution. MMCs hence require customized dc-SQUIDs. In this respect, DELight is in a unique situation: As commercial SQUIDs are avaiable only with a limited range of input coil inductances and are mostly optimized for applications at 4.2 K, they often does not fit for cryogenic detector readout. As a result, the ultimate performance of an experiment may not be reached. In contrast, the DELight collaboration combines all expertise to develop both, cutting-edge energy- and time-resolving MMC-based wafer calorimeters as well as tailored readout SQUIDs. In this way, a full-fledged detector can be developed.

Prelimininary work. S. Kempf and C. Enss have been closely working together for more than 15 years. Initially, S. Kempf passed through several academic career stages in C. Enss' department at Heidelberg University, until he was appointed as W3-professor at KIT in 2020. Since then, they continue to work exceedingly closely together via various common research projects as well as their involvement in the Center for High-resolution Superconducting Sensors (HSS) at KIT (see Sec. 4.10).

During the time in Heidelberg, S. Kempf established the research group *Superconducting Electronics*. He focused on the development of Josephson tunnel junction (JJ) based superconducting electronics devices [9], in particular dc-SQUIDs [10] and on cryogenic SQUID multiplexers [11–13] for MMC readout. These SQUIDs were and are still applied in various experiments such as the "Electron Capture in Holmium-163 experiment (ECHo)" [14], the "Microcalorimeter Arrays for X-ray Spectroscopy (maXs)" [15] detector system or prototype detectors for the "International Axion Observatory (IAXO)" [16]. Moreover, S. Kempf researched, again in collaboration with C. Enss, low-frequency noise in superconducting quantum devices [17] as well as fundamental detector properties of MMCs such as the reliability and easiness of energy calibration [18] or the detection mechanism for massive particles [19] and developed MMCs for radionuclide metrology [20] and high-resolution X-ray spectroscopy [4]. The latest X-ray detector developed shortly before moving to KIT is presently setting the world-record in terms of energy resolving power for soft and tender X-rays [4]. With respect to photon detection, S. Kempf and C. Enss have been furthermore involved in the determination of the isomer energy of ^{229}Th [21] as well as detector development for nuclear safeguards and forensics [22].

At KIT, S. Kempf continues to develop superconducting electronics as well as MMC-based detectors for radionuclide metrology. However, his focus also shifted towards the development of quantum detectors for X-ray spectroscopy at synchrotron light sources, microcalorimeters for a next-generation KATRIN-like neutrino mass experiment as well as low dark matter detection within DELight [23]. The on-going activities of C. Enss at Heidelberg University are still very manifold and cover not only the development and application of MMC-based detector systems, but also the investigation of atomic tunneling systems in amorphous solids and the development of SQUID-based noise thermometers for ultra-low temperatures.

For all the above applications, customized magnetic microcalorimeters and SQUID-based readout systems have been developed. Moreover, full detector systems have been assembled or are under construction including the engineering of cryogenic wiring, SQUID modules, readout electronics as well as the cryogenic detector assembly. A recent example is S. Kempf's project "QUASY - Quantum Sensor Platform for Synchrotron X-ray Spectroscopy" that aims at implementing a MMC-based detector for soft and tender X-ray spectroscopy at the KIT Light Source. There is hence a huge expertise in developing fully-fledged MMC-based detector systems. With respect to MMC-based wafer calorimeters, S. Kempf and C. Enss have both been involved in the development of a prototype detector for LUMINEU that comprises a distributed paramagnetic temperature sensor (cf. Sec. 2.3) that is attached by normal conducting phonon collectors [7].

2 Objectives and work programme

2.1 Anticipated total duration of the project

The total duration of this project is fully aligned with the timeline of DELight phase-I as described in Sec. 2.2 of the "Overall Description of the Research Unit and the Coordination Proposal". The anticipated total duration of the project is four years.

2.2 Objectives

DELight Project 2 is devoted to the design, fabrication, installation, calibration, and operation of the DELight detector system. This includes the design of the MMC-based wafer calorimeters and the dc-SQUID-based readout system, wafer calorimeter batch fabrication, mounting of the individual calorimeter modules forming the detector, the integration of the modules into the helium cell, the characterization of the interplay between cell and detector system, and the first science run. Moreover, dedicated R&D towards phase-II will be performed to prepare the extension as well as the sensitivity enhancement of DELight within phase-II. As Sec. 2.3 gives a detailed description of all wafer calorimeter components as well as the individual work packages and tasks to be performed, we restrict this section to an overview of the DELight detector system.

Each DELight wafer calorimeter will consist of an absorber that either adheres ^{4}He atoms evaporating from the superfluid, absorbs scintillation photons or quenches triplet helium excimers. The absorber will be formed by a high-purity sapphire (or Si) substrate, the size of which is to be determined, that is attached to a paramagnetic temperature sensor. The sensor will be magnetized by a persistent current running within a superconducting coil that is located beneath the sensor. The coil simultaneously acts as pickup coil for the magnetic flux change resulting from a temperature rise of the sensor upon an energy input. The absorbers will be equipped with a heater arrangement that is used to get rid of the superfluid helium film after starting the film burner as well as for in-situ energy and detector response calibration. Moreover, large-area superconducting phonon collectors will be distributed over the absorber surface to convert the athermal phonon population generated by the energy input into quasiparticles heating up the temperature sensor. This *athermal detection mode* will not only enhance the speed of the wafer calorimeters, but will also relax the restrictions on absorber heat capacity. The wafer calorimeters will be thermalized via a metallic thermal link to the associated calorimeter mount. In the simplest scenario, this link will be formed by an Au pad on the absorber surface and some normal conducting bonding wires. Nevertheless, more sophisticated arrangements such as highly-conducting electroplated Au posts that are pressed against the calorimeter mount will be investigated. Overall, each MMC-based wafer calorimeter will achieve an energy resolution in the range of 5-6 eV, resulting in an energy threshold $\mathcal{O}(20\,\mathrm{eV})$. For DELight phase-II, dedicated R&D will performed, eventually allowing an energy threshold of $\mathcal{O}(5\text{-}10\,\mathrm{eV})$.

Each wafer calorimeter will be read out by a dedicated two-stage dc-SQUID that is operated with a direct-coupled high-speed SQUID electronics with flux-locked loop (FLL). For this, customized first-stage SQUIDs will be developed that are impedance-matched to the wafer calorimeters. The first-stage SQUIDs will be voltage-biased to minimize their Joule power dissipation and connected via superconducting wiring to customized SQUID amplifier modules mounted outside the helium cell to boost the first-stage SQUID signals above the input noise floor of the readout electronics. They will be equipped with a heater arrangement that allows to apply heat pulses to remove the superfluid helium film after starting the film burner. Using pre-assembled cabling, the amplifier SQUID modules will be connected to vacuum-feedthroughs at the top of the cryostat, the latter acting as interface to the SQUID electronics. Besides SQUID wiring, wiring harnesses for heater actuation on top of the absorbers and the first-stage SQUIDs and persistent current injection into the wafer calorimeters will be installed. These wiring harnesses will be connected to low-noise current sources that allow applying precise heater pulses and dc-currents. Moreover, we will strongly collaborate with DELight Project 5 to develop a software framework that allows both, remote and automated detector control.

After batch fabrication and assembly, the MMC-based wafer calorimeters will be mounted within the helium cell. This will allow to test the entire detector system in conjunction with the helium cell. This includes the characterization of the detector response for different filling heights of the helium cell, the investigation of directional information and energy calibration using radioactive sources. It is self-evident that all activities will be performed in closest collaboration with all members of the RU as manifold inter-dependencies exist. The design of the wafer calorimeter modules as well as the procedure for superfluid film removal, for example, must be intimately coordinated with DELight Project 1 in which the helium cell including the in-liquid and above-liquid detector platforms as well as the film burner are constructed.

2.3 Work programme including proposed research methods

DELight Project 2 is structured in four work packages, each addressing a dedicated objective stated in the previous section. The timeline of the different work packages as well as the interplay with other projects are summarized in Fig. 2.1.

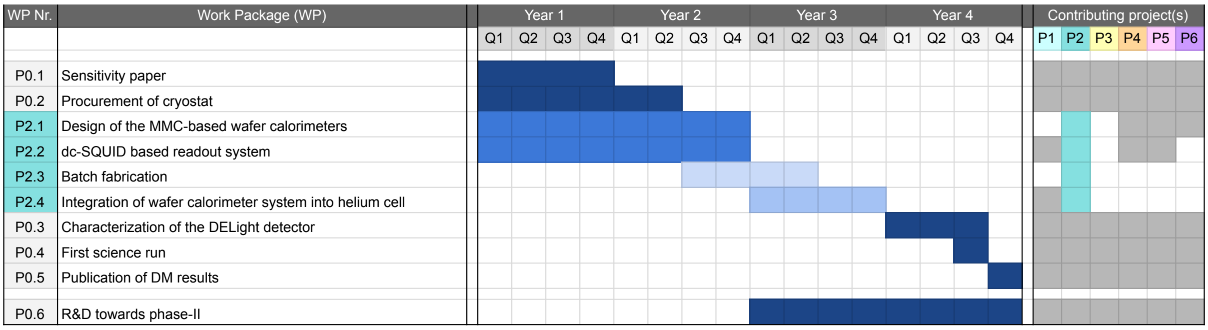

Figure 2.1: Summary of the P2 work programme. The work project (WP) numbers indicate the respective lead project (here P2) and the count within that project's list of WPs. The P0 identifier is used for WPs that are equitably performed by all participants of the RU. The shades of blue within the timeline indicate the amount of contributing projects. The lightest blue is used for WPs only conducted within P2. The darkest blue is used for WPs to which all projects P1 - P6 contribute. The rightmost block of the program signals the lead project (color) and the further contributing projects (gray).

P2.1: Design of the MMC-based wafer calorimeters

This work package aims for developing the layout of the MMC-based wafer calorimeters that form the basis of the DELight detector. Though the basic design will build on previous work [7], several new features will be investigated and integrated into the calorimeter design. This includes an alternative wafer calorimeter geometry that potentially allows significantly simplifying batch fabrication, the application of superconducting phonon collectors to reduce the heat capacity and signal rise time of the wafer calorimeter, as well as the usage of sapphire absorbers to provide larger quasiparticle signal amplification and to significantly reduce the absorber heat capacity.

Integrated-detector vs. split-detector design. Large-area wafer calorimeters typically comprise all calorimeter components on a single substrate that often acts as absorber, too [7, 24–26]. Such an *integrated-detector design* (see Fig. 2.2a) is resolution-wise best, most compact, and rather insusceptible to mechanical vibrations. At the same time, it is fabrication-wise very elaborate as each wafer calorimeter requires to carry out an individual multi-layer fabrication process. A potential alternative is a *split-detector design* that relies on a large-area absorber which is connected to an *MMC thermometer chip* via normal conducting bonding wires (see Fig. 2.2b). This design greatly simplifies wafer calorimeter fabrication as many thermometer chips can be produced on the same wafer and only the large-area absorbers must be processed individually. As the latter contain only rather simple structures (phonon collectors, heaters etc.), they can be easily manufactured. Nevertheless, the split-detector design is much more sensitive to vibrations and a slowdown of the signal rise time, both effects severely affecting the energy resolution. For this reason, the split-detector design must first prove to provide the same energy resolution as the integrated-detector design. We will hence work out both designs and benchmark the performance of prototype devices against each other to decide which calorimeter design will be used for DELight phase-I.

As magnetization is a volume property (and not a transport property such as resistance), two options for the integrated-detector design arise: The total sensor volume can either be concentrated and read out by a single pickup coil [3] or segmented and read out via several pickup coils that are connected in series (see Fig. 2.2a). The advantage of the distributed sensor design is that phonons created within the substrate reach the sensor within the shortest possible time. This feature is key

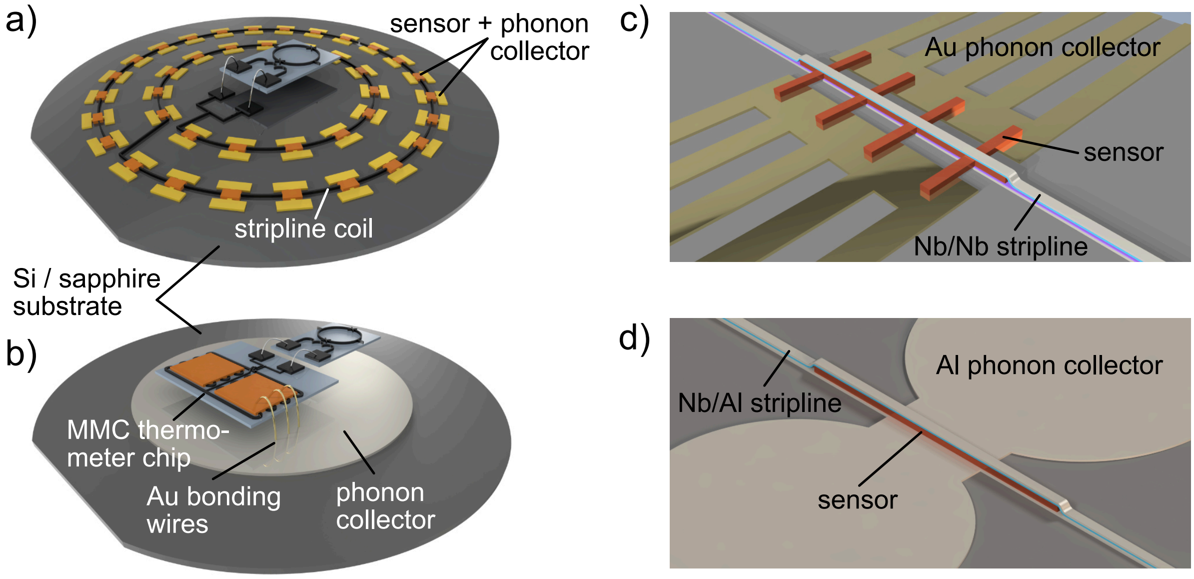

Figure 2.2: Schematic design of the **a)** integrated-detector and **b)** split-detector design. Both designs comprise a sapphire or Si substrate as absorber, phonon collectors, a distributed or concentrated paramagnetic temperature sensor (orange), and a superconducting pickup coil (black) that is connected to the readout SQUID. **c)** Illustration of a small part of an integrated-detector design comprising normal conducting phonon collectors as well as an Nb/Nb stripline that is isolated against the temperature sensor. **d)** Illustration of a small part of an integrated-detector design comprising superconducting phonon collectors as well as an Nb/Al stripline. For the latter, the Al line simultaneously acts as quasiparticle injector into the temperature sensor.

when using superconducting phonon collectors to prevent phonon back-emission into the substrate as well as to yield a fast signal rise time. However, it adds inductance and coupling losses [3], i.e. a trade-off between sensor segmentation and phonon collector geometry must be found. The integrated-detector design envisioned for DELight will be based on a spiral-like pickup coil in a stripline geometry, i.e. two insulated Nb lines will sandwich multiple sensor segments that are laterally connected to phonon collectors which are regularly distributed over the absorber surface (see Fig. 2.2d). By this, the inductance of the pickup coil can be kept at a moderate level even for structures spanning over the entire absorber. The alternative split-detector design will be based on a recent concept for radionuclide metrology that already forsees the usage of external absorbers. However, the detector parameters are not suitable for DELight, as the projected energy resolution is $\geq 20\,\mathrm{eV}$. We will hence re-optimize the detector parameters and adjust the actual detector design to the needs of DELight. These MMC temperature chip can the be readily fabricated. In both cases, i.e. for the integrated-detector and split-detector design, we will perform a full device optimization by systematically varying detector parameters and simulating signal response and noise properties using our state-of-the-art MMC models [3, 27] to ultimately minimize the energy resolution .

Superconducting phonon collectors. Existing large-area MMC-based wafer calorimeters [7, 28] comprise microfabricated Au structures as normal conducting phonon collectors. Though this technique is very effective and prevents phonon back-emission into the substrate, the existence of conduction electrons cause a large heat capacity of the phonon collectors. The phonon collectors hence significantly contribute to the total heat capacity and impact the energy resolution. Increasing the surface coverage of the phonon collectors to increase the detector speed, even worsens the situation. For this reason, the DELight wafer calorimeters will be equipped with superconducting phonon collectors made of aluminum. Since the cell (and hence detector) operation temperature will much lower than the critical temperature of Al, $T_c = 1.2\,\mathrm{K}$, the heat capacity of the phonon collectors will be exponentially suppressed and can in fact be neglected. For this reason, the surface coverage of the phonon collectors can be enlarged. This not only increases detector speed but also the efficiency of phonon collection. However, to avoid phonon back-emission into the substrate, we must find a suitable sensor-collector geometry such that the time required by quasiparticles to diffuse into the temperature sensor is smaller than the quasiparticle recombination time.

For the integrated-detector design, superconducting phonon collectors will also allow to simplify the fabrication process as well as to increase the yield. For previous designs, the latter is impacted by a potential tear-off of the phonon collectors occurring when they climb up several layers to laterally connect to the temperature sensors (see Fig. 2.2c). For this reason, we will investigate whether the lower part of the Nb stripline can be replaced by an Al line that merge into the Al phonon collectors (see Fig. 2.2d). As long as the upper insulation layer is free from defects (this condition is required for the previous design, too), the distributed temperature sensor can be deposited without any insulation onto the Al line. In this way, the Al line is not only part of the pickup coil, it also injects the quasiparticles created within the phonon collectors into the paramagnetic temperature sensor. Overall, this geometry should allow to greatly reduce the number of fabrication steps and thus to simplify the fabrication of integrated-detector design. This might mitigate its fabrication disadvantage and large quantities of integrated detectors may become feasible.

Sapphire vs. Si substrates. The signal amplification caused by the difference between the ^{4}He evaporation energy and the ^{4}He adsorption energy on the absorber surface is a key feature of the DELight detector. For a Si substrate, the present standard material for MMC fabrication, the signal gain is about 10 [29]. For a sapphire substrate, this gain factor can be up to a factor of 2 higher [6, 30]. Moreover, since the Debye temperature and the structural integrity of sapphire is higher, the heat capacity of a sapphire absorber will be significantly smaller than of a Si absorber with the same surface area. On the other hand, MMC fabrication might behave different as lattice constant, thermal expansion coefficient, thermal conductivity etc. are different from Si, too. This is especially true for the integrated-detector design where layer adhesion, ampacity of superconducting structures, persistent current switch behavior etc. are important figures of merit. For this reason, we will investigate whether our fabrication process can be adapted to sapphire substrates with reasonable effort and whether important quality measures can be maintained. If this proves true, we will readily employ sapphire substrate for calorimeter fabrication in phase-I. If not, we will use Si substrates and postpone the process adaption to the R&D towards phase-II work package to have sufficient time to batch fabricate and assembly all wafer calorimeters. For the split-detector design, fabrication is much relaxed as only the phonon collectors and heater arrangement must be prepared. In this situation, the adaption of the fabrication process seems easily feasible and sapphire absorbers would be used for the MMC-based wafer calorimeters in both phases.

We note that sapphire does not absorb IR light, i.e. IR scintillation photons couldn't be measured even if the energy resolution of the detector would be sufficient. For phase-I this will not be an issue as the energy resolution will be about 5-6 eV. However, we plan to enhance the energy resolution of the calorimeters within phase-II. We will hence look into optical substrate coatings or the usage of silicon-on-sapphire (SoS) substrates to combine both, the advantages of using sapphire substrate and the possibility to detect IR scintillation photons.

Helium cell for prototype development and wafer calorimeter characterization. To benchmark prototype calorimeters as well as to perform basic functionality tests of a randomly selected calorimeters from batch fabrication, we will install a small helium cell without film burner and heat flush purifier (see DELight Project 1) in the ^{3}He/^{4}He dilution refrigerator at KIT. This cell will also be used checking different versions of the in-liquid calorimeter assembly for vibrations, weak points or other systematic effects.

P2.2: dc-SQUID based readout system

The DELight wafer calorimeters will be read out via a two-stage dc-SQUID-based readout system that will be developed within this work package. This includes all required components, i.e. first-stage SQUIDs to be connected with the wafer calorimeter pickup coils (see Fig. 2.2), amplifier dc-SQUID arrays for boosting the first-stage SQUID output signals, the entire SQUID wiring as well as the installation and automation of the readout electronics. All components has to be matched to each other to facilitate the best possible energy resolution of the MMC-based wafer calorimeters. Moreover, the construction of the readout system must take into account the geometrical constraints set by the in-liquid and above-liquid detector platforms, the film burner as well as the stringent background requirements. For this reason, the planning of SQUID wiring will be performed in closest collaboration with DELight Project 1.

First-stage dc-SQUIDs. To avoid magnetic coupling losses, the input inductance L_{in} of the first-stage SQUIDs must be matched to the total inductance L_{MMC} of the wafer calorimeters. The latter is set by the calorimeter design and forms an input parameter for SQUID development. Starting from this value, we will develop a first-stage SQUID design that builds on previous work [10]. Though the basic design is hence straightforward, we must revise the coil arrangement and include dedicated damping structures that are key to suppress SQUID resonances that potentially spoil the SQUID performance. Moreover, we must include a heater arrangement that allows to apply heat pulses to remove the superfluid helium film after starting the film burner. Within the design process, we must bear in mind that two different calorimeter designs (integrated-detector and split-detector design) will be investigated and that both variants require different input inductances. Similar to [31], we will hence develop a flexible SQUID design, e.g. using an intermediate double flux transformer [32], that allows matching the SQUID to both calorimeter variants. We will model the SQUID design as well as the dimensioning of the required damping structures using commercial and custom-made simulation tools. Prototype devices will then guide potential refinements of the SQUID design. Here, we will particularly investigate whether the heating procedure will spoil the SQUID performance. This iterative development process will continue until several prototype devices from one batch show the expected performance.

Amplifier dc-SQUID arrays. To apply fifty MMC-based wafer calorimeters within phase-I, and, at the same time, to keep the cost per readout channel at an affordable level, DELight will employ a recently introduced scalable multi-channel dc-SQUID electronics [33]. As the noise performance of this electronics is about a factor of two worse than the performance of existing cutting-edge single-channel electronics [34, 35], existing amplifier dc-SQUID arrays can't be employed and their

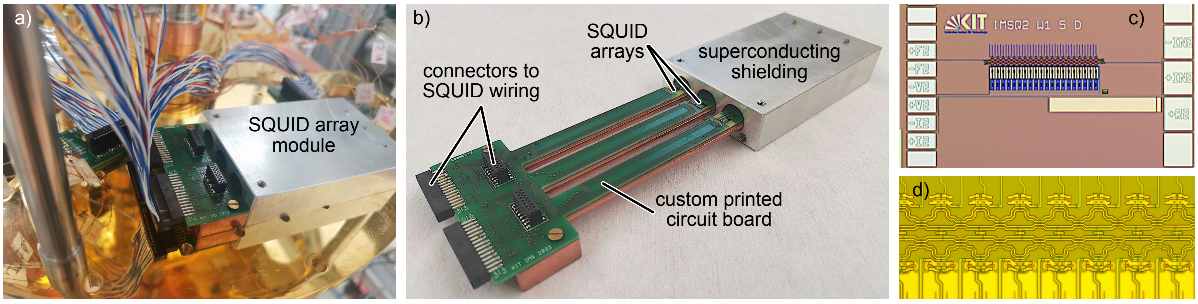

Figure 2.3: a) Photograph of a 4-channel dc-SQUID array module mounted inside a cryostat at the Institute of Micro- and Nanoelectronic Systems (IMS). For better visibility, only the readout wiring towards the room-temperature electronics is connected.**b)** Photograph of an opened dc-SQUID array module. The dc-SQUIDs are located at the end of a long custom printed circuit board that is inserted into a cylindrical superconducting shield to reduce the sensitivity of the SQUID arrays on external magnetic field fluctuations. **c)** Micrograph of a single dc-SQUID-array fabricated at IMS. It comprises 16 identical SQUID cells to impedance-match the array with the room-temperature SQUID electronics. **d)** Magnified micrograph of a part of the SQUID array showing the shape and arrangement of the individual SQUID cells.

design must be revised. The overall procedure is identical to first-stage SQUID development and will follow the same process steps. One potential challenge is that the number of SQUID cells within an arrays will have to be increased to suppress the readout noise contribution to an acceptable level. This makes the SQUID arrays rather susceptible to variations of external background fields and sets strict requirements to the shielding specifications of the amplifier SQUID modules.

Amplifier SQUID modules and SQUID wiring. For DELight, a powerful cryostat will be procured and commissioned. As this cryostat will come without wiring, we will conceptualize, fabricate and install the required SQUID readout and heater operation wiring, again in closest collaboration with DELight Project 1 as the wiring must fit into the overall helium cell and film burner arrangement. Moreover, we will engineer the amplifier SQUID modules that will be mounted at mixing chamber platform. For both tasks, we will follow our expertise gained during the installation of several SQUID systems into ^{3}He/^{4}He dilution refrigerators (see Fig. 2.3 or [36]). We will pay special attention to design of the amplifier SQUID modules that must provide sufficient magnetic shielding to operate the amplifier SQUID arrays and that should be stackable to allow for easily scaling up to wafer calorimeter count in future DELight.

Automated detector control. The usage of fifty individual MMC-based wafer calorimeters within phase-I as well as the long-term plan to increase the channel count within phase-II entails tuning several tens to some hundreds two-stage dc-SQUIDs for each measurement. Though this can still be manually done, the process is very time-consuming and the final noise performance will heavily depend on the carefulness, expertise, and experience of individuals. Moreover, a persistent current has to be injected into each sub-detector for bias field generation and the above-liquid wafer calorimeters has to be freed of the superfluid film after starting the film burner. Similarly, each calorimeter must be calibrated. Again, these tasks that can be manually made, but they are time-consuming and susceptible to the carefulness, expertise, and experience of individuals. For this reason, we will develop a software-based SQUID and detector control that enables automated SQUID tuning as well as automated detector conditioning and persistent current injection. This control software will build on existing software modules that have been created for automated SQUID characterization and will be integrated into the control system developed within DELight Project 4.

P2.3: Batch fabrication

In phase-I, the DELight detector will comprise fifty large-area MMC-based wafer calorimeters, out of which one fifth will be placed above the liquid, the remaining will be immersed in the superfluid. As the sensitive area of each calorimeter is given by size of the substrate used for calorimeter fabrication, the still rather moderate number of wafer calorimeters nevertheless requires processing fifty individual substrates. This implies either processing up to ten individual layers on each substrate (integrated-detector design) or fabricating several tens of MMC-based thermometer chips on a single substrate and equipping fifty absorber substrates with phonon collectors as well as the heater arrangement (split-detector design). From a fabrication point of view, both detector variants imperatively require batch fabrication of a large number of calorimeters with ideally identical properties. Here, the Center for High-resolution Superconducting Sensors (HSS, see Sec. 4.10) comes into play that will enable to manufacture these large quantities. To prepare for batch fabrication, the fabrication process of the selected calorimeter variant (integrated-detector design or split-detector design) must be adapted to HSS machinery and qualified by checking the properties of prototype calorimeters. As soon as the process qualification will show that the properties are within the DELight specification, batch fabrication will start and last until the required calorimeter count is produced.

P2.4: Integration of wafer calorimeter system into helium cell

In this work package, the individual MMC-based wafer calorimeters will be assembled to calorimeter modules and mounted at the detector platforms within the helium cell. Moreover, the wiring between the first-stage SQUIDs and the amplifier SQUID modules must be installed, routed within the helium cell and connectorized to allow for easy mounting and unmounting of individual calorimeters that are placed above the liquid. Similarly, the calorimeters within the superfluid will be mounted at the detector platform and connected to the electrical feedthroughs in the walls of the helium cell. This work package will be carried out in closest collaboration with DELight Project 1 as a seamless interplay between all cell and detector components are key for the success of the experiment.

P0.1-6: Procurement of cryostat, detector characterization, first science data, DELight publications, R&D towards phase-II

The work packages P0.1-6 have no leading project but are equitably performed by all participants of the RU. They are an expression of collaboration within the entire RU and thrive on the strong synergies between the projects. The activities of the RU during phase-I of DELight are framed by two main publications, a sensitivity paper (P0.1) at the beginning of the funding period and the publication of the first science results (P0.5) at the end of the funding period. These publications require input from all projects and expertise from all members of the RU and will help shape the science output of DELight. Several additional publications are planned to be published within the funding period. The cryostat is part of the coordination project and its procurement (P0.2) will be carried out by the RU together, just like the characterization of the whole DELight detector (P0.3) and the DELight operations and monitoring of the data taking during the first science run (P0.4).

In parallel to phase-I, the RU will jointly start R&D towards phase-II (P0.6). A few key contributions of DELight Project 2 will be highlighted in the following.

Characterization of helium cell and detector system. This task aims for a comprehensive characterization of the entire system. The project team will particularly study the detector response at various working points, measuring the signal response for photons and evaporated ^{4}He atoms as well as noise spectra, checking for the slow-control and automated detector operation, measuring backgrounds etc. The acquired data will be required to get a full understanding of the detector as well as to prepare the analysis pipeline.

Energy and detector response calibration. Energy and detector response calibration is a very special challenge for DELight as in a low-background measurement, calibration sources can't be permanently mounted in the target volume. On the other hand, the construction of a mechanical system that allows temporarily inserting calibration sources into the cell is very sophisticated as this system must cross the hermetic helium cell and must not bring in a noticeable heat input. For this reason, we will implement an *ex-situ/in-situ* calibration scheme. Here, all wafer calorimeters will be equipped with a microfabricated heater arrangement that allows applying well-defined heater pulses to the absorber. In a measurement prior to an actual science run, we will mount radioactive sources within the helium cell to determine the length and amplitude of heater pulses that are required to mimic signals as caused by calibration sources. These parameters only depend on the heater resistance, the latter can be checked in-situ during a science run. Detector calibration will be done by regularly applying heater pulses to the individual calorimeters and measuring the signal height.

First science run and data analysis. During the first science run(s) of DELight, all members of the RU will operate, monitor, and maintain the experiment as only a smooth interplay between cryostat setup, site and infrastructure, film burner, detector, data acquisition and computing, background understanding, and science analysis guarantees for the acquisition of science-grade data. During this period, DELight Project 2 will particularly take care of the detection system. This includes repeatedly checking for working points, looking for detector drifts or chances in signal size and noise spectra, repeatedly calibrating the energy scale as well as performing background measurements. All these data will finally be required to analyse the acquired signal traces.

R&D towards phase-II. With respect to R&D towards phase-II, DELight Project 2 aims for (i) improving the energy threshold by enhancing the energy resolution of the wafer calorimeters, (ii) full detector coverage of the entire inner surface of He cell, (iii) reducing backgrounds, and (iv) improving the sensitivity by enhancing calibration, introducing a fiducial volume and potentially using directional information. To reach these ambitious goals, dedicated R&D efforts towards phase-II must be performed during phase-I. Within DELight Project 2, the efforts starting already within phase-I include the miniaturizing the calorimeters to improve their energy resolution and to better resolve directional information, the development of a SQUID-based multiplexing technique for enabling increasing the detector count as well as investigating a method to reduce intrinsic detector background. Other tasks must be work out, too, but are not important input parameters for a follow up proposal. For this reason, they are postponed to the actual phase-II.

- **Sub-detector miniaturization:** The energy resolution ultimately depends on the total heat capacity of the calorimeter, i.e. improving the energy resolution will come along with a reduction of heat capacity. As sapphire is in many respects already the best choice as the absorber material, this will require calorimeter miniaturization. Our ambitious plan is not only to be able to resolve scintillation IR photons but also to enhance the sensitivity such that the arrival of only a few ten to hundred ^{4}He atoms can be resolved. Moreover, we will implement the concept of *coded aperture arrays* [37] for the calorimeters above the liquid to get directional information from the burst of evaporated ^{4}He atoms. Both advances will be key for enhancing the sensitivity of DELight within phase-II.

- **SQUID-based multiplexing technique:** In phase-II of DELight the number of calorimeters will significantly increase. This results on one hand from the calorimeter miniaturization and on the other hand from the intention to cover the entire inner surface of helium cell with calorimeters. As the space within the capillary through the film burner is limited, the number of wires feed through this capillary must be restricted. Ultimately, this limits the detector count if not changing the readout strategy. In this respect, we will comprehensively analyze the measured detector response and noise spectra acquired during cell and detector characterization. This analysis will reveal the strictly necessary readout bandwidth, noise level and slew-rate of the detector system. Starting from these values, we will work out a concept for a cryogenic SQUID multiplexer that allows reading out tens to hundreds sub-detectors with a single pair of coaxial cables. This development will particularly build on recent work related to the development of a microwave SQUID multiplexer as well as hybrid readout schemes (see, for example, [12, 13] or references therein).
- **Reduction of intrinsic detector background:** The potential existence of charged impurities within the absorbers is intrinsic background that can lead to spurious detector signals. To neutralize these impurities, charges must be created within the absorber. This can be done either by irradiating the absorbers with a radioactive source or with LED light. Both strategies has advantages and drawbacks and it is a-priori not clear which strategy turns out to be best. We will hence investigate both strategies to see whether we must include fiber optics within the helium cell for phase-II or whether the mounting of a strong external source is sufficient.

2.4 Handling of research data

The same text applies as in Sec. 2.3 of the “Overall Description of the Research Unit and the Coordination Proposal”.

2.5 Relevance of sex, gender and/or diversity

Sex and/or gender is not relevant to the research project. Though we strive for a diverse group of researchers, the level of diversity is also not relevant to the research project.

3 Project- and subject-related list of publications

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[5] S.J. Smith *et al.*, "Small Pitch Transition-Edge Sensors with Broadband High Spectral Resolution for Solar Physics," *J. Low Temp. Phys.*, vol. 167, no. 3-4, pp. 168–175, 2012. doi: 10.1007/s10909-012-0574-y

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[11] D. Richter *et al.*, "Flux ramp modulation based MHz frequency-division dc-SQUID multiplexer," *Appl. Phys. Lett.*, vol. 118, no. 12, 2021. doi: 10.1063/5.0044444

[12] C. Schuster, M. Wegner, C. Enss, and S. Kempf, "Flux ramp modulation based hybrid microwave SQUID multiplexer," *Appl. Phys. Lett.*, vol. 120, no. 16, 2022. doi: 10.1063/5.0087994

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4 Supplementary information on the research context

4.1 Ethical and/or legal aspects of the project

4.1.1 General ethical aspects

We do not anticipate any risks and/or harm to individuals or groups or the environment and/or the potential for other negative effects that might be posed by our research.

4.2 Employment status information

Last name: Kempf
First name: Sebastian
Employment status: Full professor (W3) at Karlsruhe Institute of Technology

4.3 First-time proposal data – Does not apply.

4.4 Composition of the project group

Table 2.1: Individuals who will work on the project but will not be paid out of the project funds.

Name and academic title	Employment status	Institution	Type of funding
Paid by institution			
Prof. Dr. Sebastian Kempf	Full professor (W3)	KIT	institutional
Prof. Dr. Christian Enss	Full professor (C4)	UHD	institutional
Dr. Stefan Wünsch	Staff scientist	KIT	institutional
Dr. Mathias Wegner	Postdoctoral researcher	KIT	institutional
Paid by third-party			
Dr. Fabienne Bauer	Postdoctoral researcher	KIT	EXU measure KIT Future Fields - Stage II

S. Kempf and C. Enss are leading experts in the development, fabrication, characterization and application of MMC-based microcalorimeters as well as SQUIDs. They have developed detector systems for various applications, e.g. radiation metrology, nuclear safeguards, mass spectrometry or X-ray spectroscopy. They are contributors to the center for High-resolution superconducting Sensor (HSS, see Sec. 4.10). B. v. Krosigk is a renowned expert in bolometric DM experiments with quantum sensors operating at $\mathcal{O}(10\,\mathrm{mK})$ temperatures and has important expertise in the baseline noise requirements for LDM searches. M. Wegner is postdoctoral researcher at the Institute of Data Processing and Electronics (IPE) at KIT, has strong expertise in SQUID based multiplexing techniques and micro- and nanofabrication and is presently responsible for setting up HSS. He will contribute to DELight by supporting and guiding the process development for batch fabrication of the DELight sub-detectors and SQUIDs. F. Bauer and S. Wünsch are postdoctoral researcher and staff scientist, respectively. They both have expertise in the development of cryogenic detectors and superconducting electronics and will bring in valuable expertise.

4.5 Researchers in Germany with whom you have agreed to cooperate on this project – Does not apply.

4.6 Researchers abroad with whom you have agreed to cooperate on this project – Does not apply.

4.7 Researchers with whom you have collaborated scientifically within the past three years

All respective researchers are included in Sec. 5.7 of the overall description.

4.8 Project-relevant cooperation with commercial enterprises – Does not apply.

4.9 Project-relevant participation in commercial enterprises – Does not apply.

4.10 Scientific equipment

The implementation of the DELight MMC-based wafer calorimeters requires facilities to fabricate and characterize test samples, wafer calorimeters and SQUIDs as well as full calorimeter assemblies. To this end, the applicant operates a dry ^{3}He/^{4}He dilution refrigerator, a home-made dry ^{3}He absorption-cooler with $< 300\,$mK base temperature as well as a dry 4 K dip probe cryostat. Within the ^{3}He/^{4} dilution refrigerator, a small He cell without purification system will be installed (see DELight Project 1). This cell will be used for development and benchmarking of the wafer calorimeters and SQUIDs to be placed within the liquid. As the existing dilution refrigerator must be shared with other projects, while various measurements for DELight must be done, the KIT Executive Board agreed to pay for the own share for a small dry ^{3}He/^{4}He dilution refrigerator, in case that a related proposal within the DFG Major Research Instrumentation Programme will be approved. This will potentially double the measurement capabilities at KIT and will provide extra contingency for meeting all project goals.

For micro- and nanofabrication, the applicant operates an in-house technology department (about 300 m^2) with integrated cleanroom (equivalent to DIN ISO5, not certified, about 60 m^2). Here, more than fifteen deposition and etching systems as well as two UV mask aligners and one EBL system are available for general R&D of cryogenic detectors and SQUIDs. Moreover, as scientific director of the Center for High-resolution Superconducting Sensors (HSS), the applicant has full access to HSS fabrication machinery. HSS is an outstanding center for the fabrication and characterization of high-resolution superconducting sensors that is presently built at KIT. After completion in summer 2024, HSS will provide dedicated machinery for medium- and large-volume batch fabrication of superconducting sensors, in particular MMCs and dc-SQUIDs. It will thus not only enable to produce the phase-I sub-detectors including the required readout SQUIDs but also to build the phase-II DELight detector that will consist of several hundreds to thousands of MMC-based sub-detectors that are simultaneously operated and read out using a dedicated cryogenic SQUID multiplexer.

Finally, it is worth mentioning that C. Enss' group at Heidelberg University operates several mK cryostats as well as cleanroom facilities for small-volume batch fabrication of superconducting sensors. For this reason, redundancy exists and guarantees that the project can be pursued even if key devices are down for a couple of weeks, for example due to malfunctions or outages of equipment.

4.11 Other submissions – Does not apply.

4.12 Other information – Does not apply.

5 Requested modules/funds

5.1 Basic Module

5.1.1 Funding for Staff

The following staff is requested for the successful completion of this project within DELight:

- **1 Postdoctoral Researcher for 2 yrs:** One full-time postdoctoral researcher with graduation in experimental solid state physics, ideally with previous experience in low-temperature physics or particle detection using cryogenic detectors as well as strong expertise in micro- and nanotechnology, will be hired for two years immediately after project start. He/she will work closely together with the doctoral researcher working on the MMC-based wafer calorimeters (see below) and will push forward the development of the wafer calorimeter design and assembly. This includes benchmarking the integrated-detector vs. the split-detector design, the introduction of superconducting phonon collectors as well as the usage of absorbers based on sapphire substrates. As the time for these developments is rather limited (only 18 months before start of sub-detector batch fabrication), strong expertise of the physics and manufacturing of cryogenic particle detectors is key for carrying out the work packages and tasks in time. Such expertise requires strong training and can't be expected from a doctoral researcher right after the beginning. Within the *wafer calorimeter* subgroup, the postdoc will spent particular emphasis on the adaption of the fabrication process to sapphire substrates as well as to the HSS machinery. This obviously includes training of both doctoral researchers to be hired within this project as well as the start of batch fabrication.

  The DFG Personnel Rates for 2023 foresee annual costs of 80,100 €/year for the 100% TV-L E13 position for the postdoctoral researcher, which amounts to **160,200 €** in total.

- **1 Doctoral Researcher for 4 yrs:** One doctoral student, ideally with background in experimental solid state physics, low-temperature physics, or superconducting quantum technology, will be hired for the full funding period. He/she will work closely together with the postdoc working on the MMC-based wafer calorimeters (see above). During sub-detector development, the doctoral researcher will work on the introduction of superconducting phonon collectors for both calorimeter variants. This includes the detector optimization with respect to trade-off between sensor distribution and phonon collector arrangement for the integrated-detector design, and the distribution of the phonon collectors for the split-detector design. Moreover, he/she will be trained by the postdoc for wafer calorimeter manufacturing on the HSS machinery to ultimately take over this responsibility and will engineer the heater arrangement for the ex-situ/in-situ detector calibration as well as the removal of the superfluid film after starting the film burner. With respect to R&D towards phase-II, the doctoral researcher will investigate coded aperture detector arrays using simulation tools and will work out a concept for the reduction of intrinsic detector background.

The DFG Personnel Rates for 2023 foresee annual costs of 55,575 €/year for the 75% TV-L E13 position for the doctoral researcher, which amounts to **222,300 €** in total.

- **1 Doctoral Researcher for 4 yrs:** One doctoral student, ideally with background in experimental solid state physics, low-temperature physics, or superconducting quantum technology, will be hired for the full funding period. He/she will work on the SQUID readout for DELight including the development of the first- and second-stage dc-SQUIDs, the amplifier SQUID modules, the SQUID heater arrangement for superfluid film removal, the SQUID wiring as well as SQUID tuning automatization. Moreover, the doctoral researcher will be trained by the postdoc as well as HSS staff for SQUID and wafer calorimeter manufacturing using HSS machinery to manufacture all required SQUIDs. As very likely one or two SQUID wafers might be sufficient to cover the entire need for phase-I, the doctoral researcher will contribute to wafer calorimeter batch fabrication, too, to share the related much heavier workload among all team members. In the second half of the project, the doctoral researcher will spent significant time for R&D towards phase-II by investigating suitable SQUID-based multiplexing techniques. The latter is essential for phase-II as the upgrade of DELight in terms of wafer calorimeter count requires in any case the application of a cryogenic SQUID multiplexer.

  The DFG Personnel Rates for 2023 foresee annual costs of 55,575 €/year for the 75% TV-L E13 position for the doctoral researcher, which amounts to **222,300 €** in total.

Both doctoral researchers will further contribute to the characterization of the DELight detector as well as the energy and detector response calibration. In closest collaboration with all members of the RU, they will perform and analyze the first science run and will contribute to the sensitivity paper, data analysis and the publication of the first results. Finally, we note that the topic for the second doctoral researcher has a very strong engineering component. In this respect, it is worth mentioning that the applicant, S. Kempf, is affiliated with both, the KIT Department for Electrical Engineering and Information Technology as well as the KIT Department for Physics, and can hence offer PhD projects in both disciplines. We will hence make sure to address students from both disciplines with the related job postings.

5.1.2 Direct Project Costs

5.1.2.1 Equipment up to € 10,000, Software and Consumables

For successful completion of DELight Project 2, resources for equipment up to € 10,000, software and consumables are required. The total costs for equipment and consumables are estimated to be **103,000 €**. Table 2.2 summarizes the breakdown of the cost. More detailed information are given afterwards.

Item 1. MMC wafer calorimeter and SQUID development involves the manufacturing and characterization of several test samples and prototype devices. For this, several consumables for sample fabrication and characterization are required. This includes Si and sapphire substrates, chemicals

Table 2.2: Overview of requested resources for equipment up to € 10,000, software and consumables.

Item	Description	Prize in € incl. VAT
1	Consumables for wafer calorimeter and SQUID development	15,000
2	Consumables for wafer calorimeter batch fabrication and SQUID manufacturing	26,000
3	Pre-assembled cables (customized) for wiring of amplifier SQUID modules	26,000
4	Amplifier SQUID modules	5,000
5	Wiring between amplifier SQUID modules and wafer calorimeters	3,000
6	Consumables for wafer calorimeters	5,000
7	InductEx software license	3,000
8	Equipment for R&D towards DELight phase-II	20,000

(photoresists, developers, solvents, substrate detergents), process gases for material deposition and etching, deposition materials, printed circuit boards as well as general consumables such as gloves, glassware, cleaners. We estimate 2,500 € per postdoc or doctoral researcher per year for the first two years, i.e. in total 15,000 €.

Item 2. Wafer calorimeter batch fabrication and SQUID manufacturing will be performed using HSS machinery. As S. Kempf and C. Enss are main contributors within HSS, the access to HSS machinery will be free of charge. Similarily, operating and maintenance costs will be covered by HSS. Nevertheless, several consumables for batch fabrication are required. This includes more than fifty Si and sapphire substrates, chemicals (photoresists, developers, solvents, substrate detergents), process gases for material deposition and etching, deposition materials, printed circuit boards as well as general consumables such as gloves, glassware, cleaners. We estimate 26,000 € for the production of fifty wafer calorimeters.

Item 3. The wiring between the multi-channel SQUID electronics and the amplifier SQUID modules requires robust pre-assembled cables (connectorized thirty CuNi wires in a woven nomex matrix) as well as vacuum-tight feedthroughs. We aims for a total of sixty channels, out of which fifty will be used for sub-detector readout and ten for heater actuation, persistent current injection as well as detector response and energy calibration. The estimated costs are 26,000 € for twenty wiring harnesses, each equipped for three channels.

Item 4. The assembly of the amplifier SQUID modules requires soft-magnetic shielding compatible with cryogenic temperatures, customized printed circuit boards as well as connectors. The estimated costs are 5,000 € for a total of fifty amplifier channels.

Item 5. To connect the amplifier SQUID modules and the sub-detectors, home-made cables are required that fit into the overall detector assembly as well as the capillary within the film burner. For cable assembly, wire raw material as well as connectors are required. The estimated costs are 3,000 €.

Item 6. The assembly of the sub-detector modules requires radio-pure copper as well as material (sapphire balls, springs, etc.) for mounting the wafer calorimeter within the sub-detector modules. The estimated costs are 5,000 € for all calorimeter modules.

Item 7. MMC wafer calorimeter and SQUID development involves the simulation of inductances, mutual couplings as well as magnetic field sensitivities. For this, commercial and home-made software is used. For DELight, the software package InductEx will be used. The costs for a two-year license are estimated to 3,000 €.

Item 8. For preparing phase-II of DELight, R&D towards SQUID-based multiplexing techniques will be performed. This requires several passive and active microwave components (mixers, amplifiers, superconducting coaxes etc.). The estimate for the total cost for these activities is 20,000 €.

5.1.2.2 Travel Expenses

For DELight Project 2 a total of **25,500 €** travels funds are required to cover the following costs:

- **International conferences.** The attendance of and contribution to relevant international conferences such as the International Workshop on Low-Temperature Detectors (LTD), the Applied Superconductivity Conference (ASC) or the European Conference on Applied Superconductivity provides important visibility, networking, and interpersonal communication opportunities strengthening DELight and the careers of its scientists. We estimate the cost for a typical 5 day long international conference or workshop to be 3,000 € and foresee one international conference for each person funded by this RU as well as the applicant. The total amount required is thus **12,000 €**.

- **Workshop on Cryoelectronic Devices.** The attendance of the national workshop on cryoelectronic devices (KRYO) provides important networking opportunities for the doctoral researchers as well as the opportunity to discuss SQUID and microcalorimeter development with the German main players. We estimate the average costs for the attendance of this workshop to be 800 € and anticipate that each doctoral researcher can attend twice and the postdoc once this workshop. Overall, this amounts to **4,000 €**.

- **DPG Spring Meetings.** Doctoral and postdoctoral researchers, as well as the DELight project which they represent, strongly benefit from attending the annual Spring Meeting of the DPG (German Physical Society) every year. Especially doctoral researchers use this opportunity for their first presentations to the wider scientific community. We estimate the costs for a 5 day long trip to the DPG Spring Meeting at a Germany city at 750 € and plan with ten trips during the funding period, which amounts to **7,500 €**.

- **DELight in-person meetings.** This project is tightly connected to several other DELight projects and hence requires close coordination with our colleagues. Moreover, the installation of the sub-detector modules within the DELight cryostat must be performed on-site. Overall, this requires occasional travel to other institutions for day-long in-person meetings. Here we can clearly benefit from the close geographical proximity of the three DELight institutions. We estimate the average costs for a short trip at 100 € and anticipate a total of twenty trips including those for sub-detector mounting. This amounts to **2,000 €** in total. (The costs for traveling to or hosting the two in-person collaboration meetings per year are covered by the Coordination Project.)

5.1.2.3 Visiting Researchers (excluding Mercator Fellows) – Does not apply.

5.1.2.4 Other Costs – Does not apply

5.1.2.5 Project-related Publication Expenses

Does not apply. Project-related publications will be published in journals of the Sponsoring Consortium for Open Access Publishing in Particle Physics (SCOAP^3) where no extra costs occur. Moreover, KIT has several arrangements with publishers such as AIP Publishing, IOP Publishing or Springer Open Choice (DEAL) that allows KIT corresponding authors to publish their articles under an open access licence without additional charges. This particularly the main journals for cryogenic particle detector, i.e. Journal of Low Temperature Physics, Applied Physics Letters, Journal of Applied Physics, and Superconductor Science and Technology. In addition, all articles will be posted on the open-access `arXiv` preprint server.

5.1.3 Instrumentation

5.1.3.1 Equipment exceeding € 10,000

For successful completion of DELight Project 2, resources for equipment exceeding € 10,000 are required. The total cost is estimated to be **51,000 €**. Table 2.3 summarizes the breakdown of the cost. More detailed information are given in the item description afterwards.

Table 2.3: Overview of the requested resources for equipment exceeding € 10,000.

Item	Description	Prize in € incl. VAT
1	Two three-channel high-speed FLL SQUID electronics for sub-detector R&D (Magnicon GmbH, Type XXF-1-6/3)	30,000
2	Two three-channel current source systems for heater actuation, bias current injection, persistent current switch actuation, and detector calibration (Magnicon GmbH, Type CSE-2/3)	21,000

Item 1: The development of the MMC wafer calorimeters, the related sub-detector design and assembly as well as the readout SQUIDs requires two flexible three-channel high-speed FLL SQUID electronics for prototype characterization and performance estimation. These electronics will be shared among the postdoctoral and doctoral researchers hired within project P2. They must be easily interchangeable for measurements in 4 K dip probes as well as the available ^{3}He/^{4}He dilution refrigerator(s) and must provide full control over all parameters of a two-stage dc-SQUID setup. For this reason, the multi-channel SQUID electronics to be used for operating the DELight detector is not suitable as it is not easily movable and doesn't allow to independently control all parameters of a two-stage dc-SQUID setup.

Item 2: Within the DELight detector, resistive heaters are used for superfluid film removal from the sub-detector modules, persistent current switch actuation as well as ex-situ/in-situ calibration of the detector response and energy scale. Moreover, bias currents must be injected into the pickup coils to magnetize the paramagnetic temperature sensors. Overall, this requires two three-channel current source systems, each equipped with three bipolar $\pm 150\,\mathrm{mA}$ sources for bias current injection as well as twelve unipolar $20\,\mathrm{mA}$ for heater actuation. In the first two years, these current source systems will be used by project P2 for MMC wafer calorimeter and SQUID development. Later, the systems will be transferred and permanently installed at the DELight cryostat for detector operation and characterization as well as all subsequent science runs.

5.1.3.2 Major Instrumentation exceeding € 50,000 – Does not apply.

P3 - Low-background environment

Applicant: Marc Schumann (Freiburg)
Co-applicants: Klaus Eitel (Karlsruhe), Sebastian Lindemann (Freiburg)

Project Description

DELight is a new particle physics experiment that can only be realized through the confluence of all six projects. Each project plays a fundamental and unique role, where the project described in the following is responsible for achieving a **background level which is sufficiently low** for a competitive search for low-mass dark matter.

The science goal of the first phase (phase-I) of DELight [1], to be completed within the first four years of funding, is to search for light dark matter with masses $\gtrsim$60 MeV/c^2 with a 1 kg$\times$d exposure of a liquid helium (LHe) target and a 20 eV detector threshold, i.e., very close to the He atomic excitation threshold of 19.77 eV. Cross sections above a few 10^{-40} cm^2 for spin-independent dark matter-nucleon scattering will be explored. The second phase (phase-II) aims for a lower 10 eV threshold and a 100$\times$ larger exposure to improve the sensitivity by about two orders of magnitude and to explore even lower dark matter masses. Both sensitivity predictions assume a zero background scenario, i.e., no background event in the dark matter region of interest over the measurement period. This goal is commonly considered achieved if the background expectation for the given exposure is $\lesssim$0.1 event. Given that background sources are ubiquitous, with background events coming from the environment (gamma-radiation, neutrons, muons, muon-induced backgrounds) and from the detector and shielding materials themselves (alpha/beta/gamma-radiation, neutrons), such requirements place DELight into the field of low-background experiments.

The task of this project P3 is to ensure that the background requirements will be reached for phase-I while preparing for the subsequent phase-II. This will be achieved by identifying low-background materials to construct the detector and auxiliary systems close to the LHe target, by studying the depth requirements for the different phases of DELight, and by developing a scalable shield to reduce environmental backgrounds. A detailed simulation of the detector system is the basis for this task.

1 Starting Point

State of the art and preliminary work

Liquid helium (^{4}He) is not only an ideal target to search for low mass dark matter (LDM) but also very beneficial in terms of backgrounds. Helium does not have any long-lived radioactive isotopes and can be purified from all other – possibly radioactive – atoms. Thanks to their high mobility and since the walls of the LHe cell define a favorable energetic minimum, impurities freeze out at the walls at mK-temperatures [2]. This also holds for particulates and thus means that the bulk of the LHe contains no target-intrinsic background sources, which are currently dominating the background for the most sensitive searches for dark matter at higher masses [3]. The backgrounds affecting the LDM search in the first phases of DELight will only be radiation that enters the target from external sources. While conventional dark matter detectors with massive targets can exploit the self-shielding capabilities of their (usually heavy) target against external backgrounds, this is not the case for LHe with its very low atomic number $Z = 2$. Moreover, the first generations of DELight will be rather small in size and contain little mass. This renders external shielding important to reduce the background.

Background sources in LHe. The expected dark matter signal is a single- scatter nuclear recoil (NR) signal since the dark matter is uncharged and very weakly interacting. The energy region of interest for the LDM search is from the threshold at a few tens of eV to $\sim$10 keV. (The endpoint of the recoil spectrum of a 1 GeV/c^2 LDM particle in LHe is at 1.7 keV.) The dominant source of background above 19.77 eV, the lowest excited state of the He-atom below which no electronic excitation is possible, are gamma-ray induced Compton scatter and photoabsorption processes which produce electronic recoils (ER). The gamma-rays come from contaminations of detector components with isotopes of the ^{238}U and ^{232}Th decays chains, the long-lived ^{40}K and anthropogenic isotopes such as ^{137}Cs and ^{60}Co.

Based on the expected partitioning of the recoil signal into the different detectable quanta (scintillation photons: from singlet and triplet states as well as IR photons; quasiparticles: phonons, rotons), the HeRALD project studied the potential to discriminate between ER and NR signals based on the quasiparticle/scintillation signal ratio, taking into account reasonable fluctuations [4]: the predicted ER rejection power (at 50% NR acceptance) improves quickly with recoil energy, starting from essentially no power at $\sim$20 eV close to the energy threshold to leakage fractions of $\sim 10^{-6}$ at 1 keV. While ER rejection in LHe was not yet demonstrated experimentally we anticipate that this ER rejection mechanism will relax the radiopurity requirements. DELight will in principle be able to detect and subsequently reject background multiple-scatter signatures thanks to the low phonon velocity of 240 m/s in LHe and the large number of MMC channels around the target: a 20 mm spatial separation corresponds to $\sim 100\,\mu$s time difference. However, no large gain in gamma-background reduction is expected because of the gamma's rather long mean free path in LHe and the small size of the LHe cell. This means that the gamma backgrounds have to be reduced by selecting low-background materials for detector construction (*avoid* backgrounds) and by surrounding the detector with a massive shield (*shield* backgrounds).

MeV-scale gamma rays, e.g., from ^{40}K or ^{208}Tl from the ^{232}Th decay chain, can also coherently scatter off the helium nuclei and produce low-energy nuclear recoils [5]. The dominant process leading to nuclear recoils above $\sim$10 eV is nuclear Thomson scattering. However, its background contribution, assuming typical radioactive contaminations for the construction materials, remains well below the contribution from coherent elastic neutrino-nucleus scattering (CEνNS, see below) and will be highly exceeded by ordinary gamma backgrounds. At very low energies (1 eV), Rayleigh scattering will dominate the background budget; Delbrück scattering is subdominant. While gamma-induced NRs might become relevant for future LHe projects aiming for very low thresholds and very large exposures, it is irrelevant and can thus be neglected for the first phases of DELight.

Neutrons are uncharged and thus interact with the helium nuclei producing nuclear recoils – as expected from dark matter interactions. In principle, neutrons could be identified based on multi-scatter signatures. However, due to the long mean free path of the MeV-scale neutrons relevant here, tagging these signatures will hardly help to reduce the neutron background. Background reduction thus also mainly relies on material selection and neutron shielding. Neutrons have two different origins: *cosmogenic neutrons* are created by muons with mean energies >40 GeV. Muons of these energies enter in underground laboratories and interact with the detector and the laboratory environment. The neutrons are produced in hadronic or electromagnetic showers; in the latter case, the main process is photoneutron production by real photons. The produced neutrons have energies up to the GeV-range and a great penetration power. *Radiogenic neutrons* are created in (α, n)-reactions where an α-particle, usually from a decay in the primordial decay chains, is absorbed by a nucleus and knocks off a neutron. This production process is highest for low-Z materials; very heavy nuclei can essentially only generate neutrons via spontaneous fission due to their high Coulomb barrier preventing (α, n)-reactions. The highest contributions usually come from ^{238}U and ^{235}U present in materials.

Single-scatter nuclear recoils are also produced by coherent elastic neutrino-nucleus scattering (CEνNS) of solar (mainly ^{8}B, hep) as well as atmospheric neutrinos. As neutrinos cannot be avoided or shielded, this process represents an irreducible background for the LDM search [6]. (Some background rejection would be possible if the direction of the incoming particle could be reconstructed [7].) CEνNS will not be a significant source of background in the first phase of DELight, however, depending on the eventually achieved ER rejection level, it might become relevant already in the second phase.

Another possible source of background, albeit much harder to predict before a detector is actually constructed and operated, are detector artefacts. These might originate in vibrational or electromagnetic noise which can cause significant signals given the low energy threshold foreseen for the LDM search. An excess of such signals (of yet unknown origin) has been observed below O(100) keV by many dark matter experiments using crystal detectors (e.g, CRESST, EDELWEISS, NUCLEUS, SuperCDMS and others), see [8]. CRESST-III could recently reject the hypothesis that this excess is caused by dark matter, radioactive contamination and sources intrinsic to the crystal bulk [9]. Artefacts might also come from incomplete signal collection of regular radioactivity-induced events, especially at the LHe-cell boundary. This can be minimized by a very high MMC sensor coverage surrounding the target, plus position reconstruction that can be used for target fiducialization. It was shown in [4] that pile-up due to the rather slow LHe+MMCs detector is no issue.

Background mitigation. Background can be mitigated and low-background environments for dark matter searches established in various ways, see, e.g. [10]. Here we focus on LHe and in particular DELight.

Dark matter detectors are installed inside massive shields to suppress external backgrounds originating from the experiment's environment. High-Z materials, e.g., lead and copper, but also large amounts of (cheap) water, are efficient against external gamma rays. Dense materials with a high hydrogen content (e.g., polyethylene or paraffin) as well as water efficiently moderate and eventually absorb neutrons. (The absorption rate can be increased by adding materials with a high cross-section for neutron capture, e.g., ^{157}Gd.) In order to reduce muon-induced neutrons, dark matter detectors are installed in deep-underground laboratories and – if required – additionally equipped with active muon veto detectors. For the first phases of DELight, a massive compact shield will be designed and built in collaboration with P1 and P4. At least for phase-II, the science run is planned to take place in a shallow underground laboratory (see P4).

As the detector components themselves are usually a source of background, more events are expected close to the boundary/surface of a detector; if the interaction position of an event can be reconstructed, this background can be reduced by considering only the inner part of the active target for the dark matter search (fiducialization). Given the low mass number and hence little self-shielding power or LHe, fiducialization in DELight will mainly mitigate beta and alpha backgrounds from the cell walls.

An effective shield will usually render the "external" background from the detector surroundings negligible (with the exception of neutrino-induced backgrounds). The main remaining background comes from the detector and the shield itself. This "material background" can be reduced by using only materials and components with a low intrinsic radioactive contamination for detector construction. Dedicated material screening facilities are used to identify suitable materials and components; these include low-background gamma spectrometers, mass spectrometers, facilities for neutron activation analysis, Rn emanation as well (surface) alpha-spectroscopy. Low-background materials for DELight will be identified using the instruments available at the University of Freiburg.

In many cases the dark matter target itself has to be cleaned from radioactive impurities to reduce the material background. In case of solid targets, this is done prior to the start of the experiment, e.g., during crystal growing, to produce crystals that are significantly cleaner than the pre-selected raw material. Cryogenic distillation exploiting the different boiling points of target and background gases [11], or alternatively gas chromatography [12] are used to clean noble gas targets (e.g., from Kr). Radioactive radon (e.g., ^{222}Rn as a daughter of the ^{238}U chain) is constantly emanated from surfaces and could thus enter liquid or gaseous dark matter targets. Its removal requires constant online methods, e.g., cryogenic distillation [13]. As cryogenic helium is intrinsically pure since all impurities freeze out at the detector walls, none of this methods will be required for DELight.

Active background rejection methods exploit knowledge on the expected dark matter signal: due to the low cross section, it will only scatter once in the detector (single scatter signature) and it will interact with the neutral but massive nucleus, producing a nuclear recoil signal. The selection of single scatter nuclear recoils in the analysis process, by means of the quasiparticle/scintillation signal ratio, is expected to be possible in DELight and thus effectively reject backgrounds.

Background rates in dark matter detectors. So far, no fully functional LHe-based dark matter detector has been built and operated. Therefore there is also no state-of-the art for the achieved background rates. A LHe-based dual-phase time projection chamber (TPC) was proposed in [14]; it was targeting significantly higher thresholds at the keV-scale and the background expectations were based on assumptions from the HERON project [2]. For HeRALD, a Monte Carlo-based background estimate exists, assuming a simplified geometry of a SuperCDMS-like shield and the environmental neutron flux of LZ [4]: For a 1 kg LHe detector, a total background rate of about 3 events/keV/kg/day above 19.77 eV is predicted, dominated by Compton scattering gamma events (and ignoring the possible ER rejection discussed above). Another proposal for a LHe-based TPC is ALETHEIA [15]. Its backgrounds, however, are so far only estimated in a very preliminary way by essentially scaling the background from the LZ experiment [16].

All operational dark matter projects (with targets other than LHe) are installed inside massive shields in deep-underground laboratories and are built from low-background materials. Many of them employ powerful techniques to reject ER backgrounds at analysis level. For low dark matter masses (and searches for NR signals), the most sensitive results are from the CRESST experiment, which operates gram-scale $CaWO_4$ or Si-crystals at mK-temperatures. The background rate observed in a 25 g $CaWO_4$ crystal of CRESST-III is $(7.9 \pm 0.8) \times 10^{-3}$ counts/keV/kg/day in a 100 eV-40 keV region of interest, which can be reduced by an order of magnitude by an event-by-event based rejection of gamma, beta and alpha particles [17]. (Note that the observed background rate is currently increasing towards the threshold in essentially all solid-state detectors, as mentioned above.) At high WIMP masses, the best results to date are from the multi-ton liquid xenon (LXe) TPCs LZ [18] and XENONnT [19]. With $(4.5 \pm 0.4) \times 10^{-5}$ events/keV/kg/day in the 1-30 keV (electron equivalent) region, XENONnT achieved the lowest background ever realized in a dark matter detector so far [3]; this background level was further reduced in the meantime [19]. The LZ background level is $(6.3 \pm 0.5) \times 10^{-5}$ events/keV/kg/day [20]. Both numbers are before ER rejection.

Preliminary Work. All scientists involved in this project are leading experts in the design and construction of low-background detectors and collaborate already closely within the XENON and DARWIN experiments. Marc Schumann led the overall design and construction of the XENON1T [21] and XENONnT [3] low-background liquid-xenon time projection chambers (TPC) and assembled the XENON100 TPC [22]. Sebastian Lindemann led the design, construction and assembly of the field cage of the XENONnT TPC [23]. Both scientists participated in the XENON100, XENON1T and XENONnT material screening campaigns [24–27]. Together with Klaus Eitel they are currently developing low-background electrodes for LXe TPCs.

The Geant4-based detector model of XENONnT was largely developed by the Freiburg group. It was used to inform whether the radiopurity of a material (measured in the screening campaign) was sufficient to use it at a certain location in the detector. The final model, including the measured contaminations, was used to predict the sensitivity of XENONnT [28] and serves as a basis for the

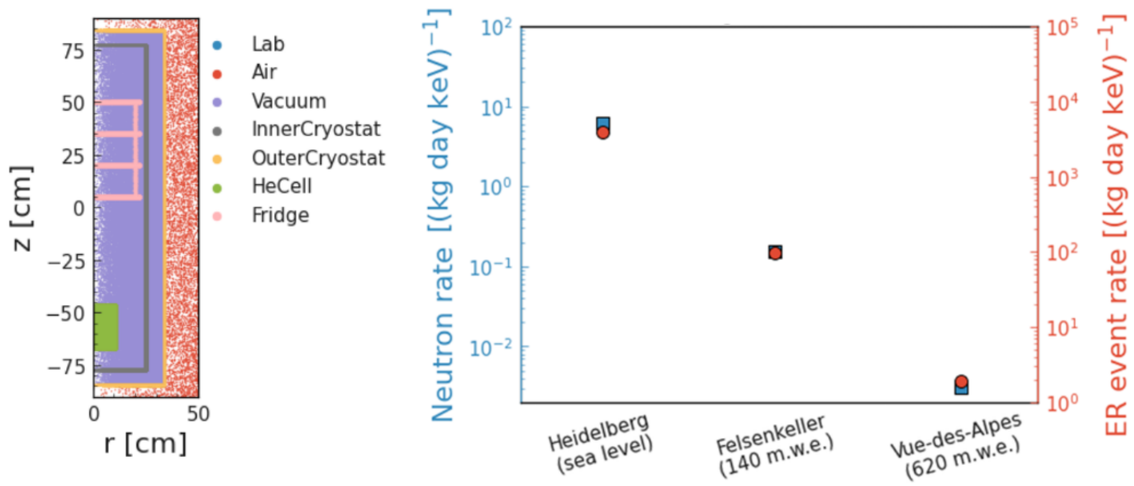

Figure 3.1: Preliminary simulations for DELight. (Left) Very simplified, rotational symmetric geometry of DELight Phase-I as constructed in Geant4. The simulated laboratory environment (Lab: concrete) and air volume around the cryostat extends well beyond the dimensions shown here. (Right) Preliminary results on the expected muon-induced neutron (blue, left axis) and muon-induced electronic recoil (ER; red, right axis) rate in the LHe cell, without any shielding (!); the region of interest is 10 eV to 10 keV of deposited energy. Installing the detector in the Vue-des-Alpes underground laboratory at a depth of 620 meters water equivalent (m.w.e.) will reduce the muon-induced (cosmogenic) neutron rate by more than three orders of magnitude and the ER rate even further.

detector signal simulation, in which the Freiburg group is still involved. Klaus Eitel has also extensive experience in detector simulations from several low-background detectors, including the EDELWEISS dark matter search [29]. The applicants have developed various low-background components for these experiments and many low-background detector components were produced in the mechanical workshops in Freiburg and at KIT.

Preliminary Geant4 simulations for DELight are shown in Fig. 3.1: a simplified geometry of the possible phase-I DELight detector (without external shielding) was used to study the impact of the depth of the laboratory on the neutron and electronic recoil event rate. The installation of DELight in the rather shallow Vue-des-Alpes Laboratory in the Swiss Jura mountains at an equivalent depth of 620 meters water equivalent [30] (see also P4) will reduce both backgrounds by several orders of magnitude compared to above-ground operation.

The Freiburg group owns and operates the GeMSE gamma spectrometer [31, 32]. This low-background facility uses a 2 kg high-purity germanium crystal and is also installed in the Vue-des-Alpes laboratory. The design and construction of the facility was led by Marc Schumann, remote operation and the sample analysis procedure were optimized by Sebastian Lindemann during the last years. GeMSE will be used to select radiopure construction materials and components for DELight. It is installed inside a compact massive shield made of high-purity copper, low-background lead and standard lead and is combined with an active muon veto (made of large plastic scintillator panels), see Fig. 3.2. The shield was optimized using detailed Monte Carlo simulations; its massive sliding door to access the sample cavity is supported by well-designed heavy load casters on rails and can be easily opened by a single person. A similar shielding design and the same development procedure is being anticipated for DELight. Klaus Eitel is an expert in muon and neutron shielding as well as neutron detection. The EDELWEISS dark matter experiment was also installed in a massive compact shield and KIT was responsible for its muon veto [33].

Figure 3.3 shows the measured background spectrum of GeMSE: A Geant4-based simulation of the detector, using measured radioactive material contaminations as input, is able to describe

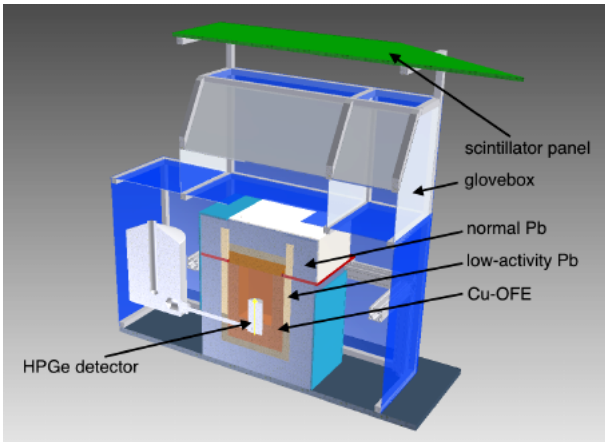

Figure 3.2: CAD rendering of the low-background gamma spectrometer GeMSE [31, 32] developed and operated by the Freiburg group. It is located in the Vue-des-Alpes underground laboratory [30]. To reduce the background rate, the high-purity germanium (HPGe) crystal inside its low-background cryostat is installed inside a massive shield made of OFE copper, low-activity lead and ordinary lead. The shield is surrounded by a glovebox and the large sample cavity is continuously purged with nitrogen gas. A muon veto made of large plastic scintillator panels is installed above and behind the sample cavity.

the data extremely well. The very low background of the facility is now limited by cosmic muons which are neither shielded by the rock overburden nor tagged by the muon veto. This demonstrates the power of simulations combined with material screening to understand and possibly optimize a detector's background level. All P3 applicants were involved in similar background studies for other dark matter experiments as well.

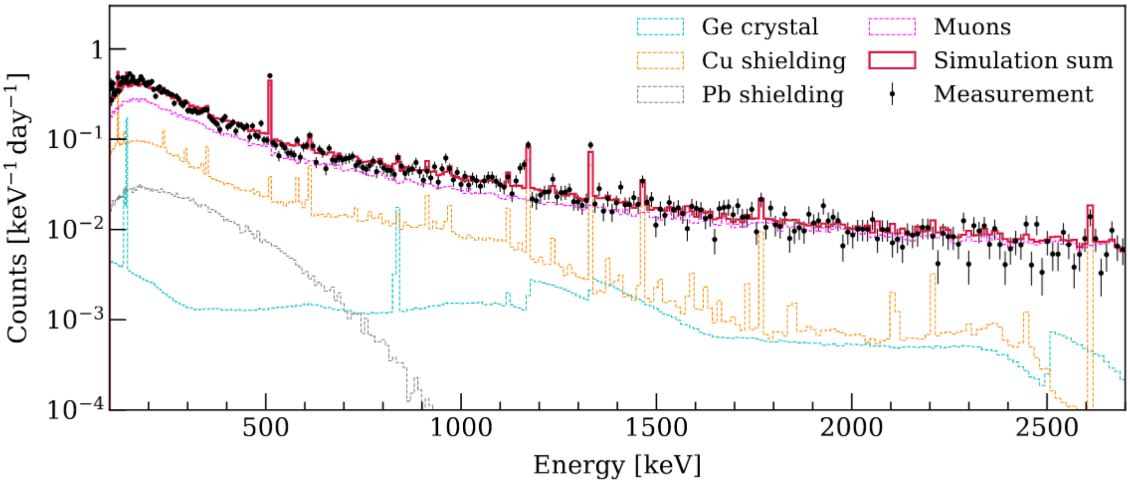

Figure 3.3: Background spectrum of the GeMSE low-background spectrometer [31, 32]. The Monte Carlo-based simulations, based on the measured radioactive contaminations of its components and a detailed detector model, enable a full understanding of the background spectrum, which is now muon-dominated (magenta). The shield of the facility (see Figure 3.2) was designed and optimized by means of Monte Carlo simulations.

Sebastian Lindemann is an expert in the analysis of trace impurities in gases [34] and in the quantification of rare background components, especially radiactive noble gases (Kr, Rn) [35]. Together with Marc Schumann he recently developed a radon emanation detector [36] which is also available for DELight in case it turns out to be useful.

2 Objectives and work programme

2.1 Anticipated total duration of the project

The total duration of this project is fully aligned with the timeline of DELight phase-I as described in Sec. 2.2 of the "Overall Description of the Research Unit and the Coordination Proposal". The anticipated total duration of the project is four years.

2.2 Objectives

Project P3 is an integral part of the overall DELight RU proposal. P3 is responsible for ensuring that the low-background environments required for a competitive first LDM search are being met and for conducting R&D towards phase-II.

The preliminary background goals compatible with the science goals, but defined without a full detector model, are shown in Fig. 3.4 for the first two DELight phases: Above 19.77 eV, i.e., down to the planned threshold for phase-I, the background will be dominated by electronic recoils (ERs) from gamma interactions. These are expected to be reduced by ER rejection based on the quasiparticle-to-scintillation signal ratio, however, due to the lack of experimental verification this

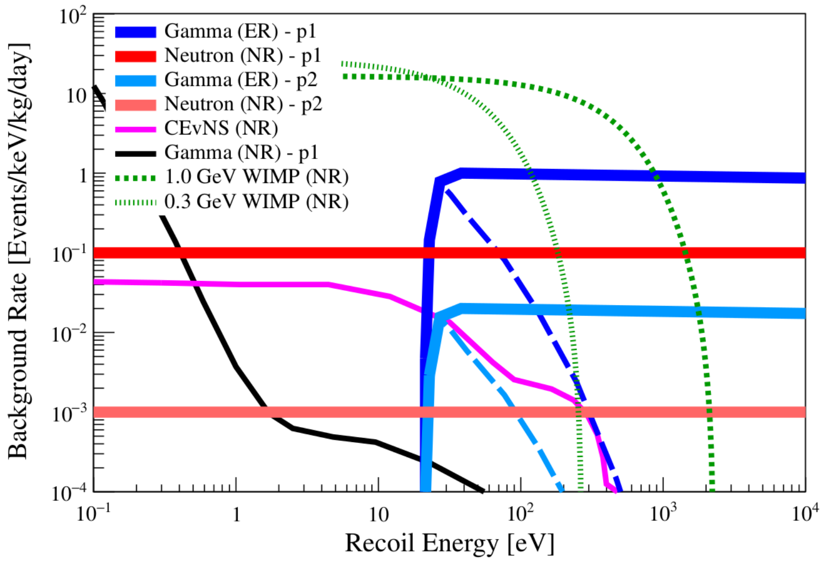

Figure 3.4: Background goals of DELight: Electronic recoil (ER) background events from gamma-interactions occur only down to recoil energies of ~20 eV and have to be reduced such that they are irrelevant in phase-I (blue, p1) and phase-II (light blue, p2). The dashed blue lines assume the – experimentally not yet demonstrated – ER rejection capability predicted in [4] which would leverage the radiopurity requirements. The goal for the background from radiogenic and cosmogenic neutrons, which produce nuclear recoil signals (NR), is sketched by the red (phase-I) and light red lines (phase-II) – these are just indicative and not from detailed simulations. The irreducible background from coherent elastic neutrino-nucleus scattering (CEνNS, magenta) starts to get relevant in phase-II. Gamma-ray-induced NR backgrounds [5] (black) are irrelevant for the planned thresholds in the upcoming DELight phases. (Data taken from [4] for reference.) The recoil spectra of 1.0 GeV/c^2 (scattering cross section $\sigma = 10^{-39}$ cm^2) and 0.3 GeV/c^2 ($\sigma = 10^{-40}$ cm^2) dark matter particles are shown for comparison (green dashed).

effect is currently not considered in the background goal. Nuclear recoils (NRs) induced by neutrons will only be a dominant background at higher energies in case ER rejection works efficiently. Coherent elastic neutrino nucleus scattering (CEνNS) will be irrelevant in DELight phase-I but dominate the background below ~20 eV down to the threshold in phase-II. Gamma-induced NRs [5] will not be a relevant source of background for the first phases of DELight.

The following tasks were identified to achieve these background goals:

P3.1 Develop a detailed model of DELight to be used in Geant4-based Monte Carlo simulations. Use simulations to inform the design of the detector (and iteratively upgrade the model).

P3.2 Assess the depth requirements for the experiment using the Monte Carlo model.

P3.3 Design and study of the mechanical shield by means of the Monte Carlo model.

P3.4 Identification of suitable low-background materials; use the simulation model to decide whether the radioactivity of a material/component at a given location in the detector is compatible with the background goals.

In addition to these four tasks, the P3 team will participate in several common DELight tasks, in particular detector construction (including cleaning of the components), commissioning and characterization, the first science run and data analysis. For the latter the detailed background model required for the dark matter inference (see P6.4) will be developed.

2.3 Work programme including proposed research methods

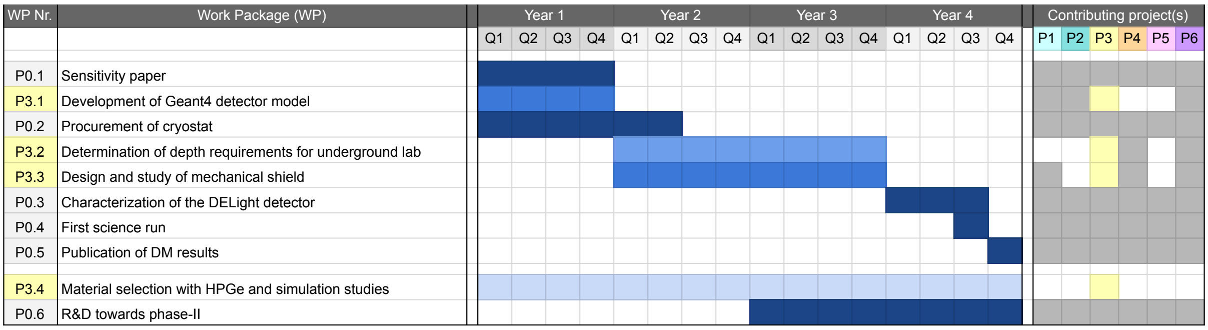

Figure 3.5: Summary of the P3 work programme. The work package (WP) numbers indicate the respective lead project (here P3) and the count within that project's list of WPs. The P0 identifier is used for WPs that are equitably performed by all participants of the RU. The shades of blue within the timeline indicate the number of contributing projects. The lightest blue is used for WPs only conducted within P3. The darkest blue is used for WPs to which all projects P1 - P6 contribute. The rightmost block of the programme shows the lead project (color) and the further contributing projects (gray).

The timeline of P3's work programme is shown in Fig. 3.5. It also shows the tasks that are equitably performed by all participants of the RU. In the following we describe the tasks lead by P3 in detail:

P3.1: Development of Geant4 detector model

The ultimate goal of this task is to have a full, detailed model of the DELight experiment in the Geant4 Monte Carlo simulation framework. Geant4 [37] is a standard tool in (astro-)particle physics that allows the tracking of particles through a detector system. Here it will be used to simulate the impact of backgrounds (e.g., particles emitted from the laboratory walls or the detector materials themselves, as well as cosmogenic particles such as muons) by tracking the particles through the detector and the simulation of their interaction with the LHe target, which will eventually create a detectable signal. In addition, the model will allow the simulation of calibration sources (see P6). In order to enable a direct comparison of the simulation with data, and also to produce a realistic background model which is required for the dark matter search (P0.3 and P0.4), the simulation needs to take into account the detector response (from P0.3).

As the DELight experiment is to be designed within the first funding period, the model will be developed in an iterative way: starting from a preliminary "best guess" design as, e.g., shown in Fig. 3.1, based on previous experience, technical requirements, dimensions inspired by possible MMC detector configurations as well as typical material contaminations, the backgrounds will be assessed. In case they are too high to meet the sensitivity goal, the design will be adapted accordingly and the achievable background will be re-evaluated. Whenever the radioactive contamination of a candidate material has been measured (see P3.4), these values will be implemented in the model which allows us to decide whether the particular material can be used in the experiment, whether the design needs to be adapted or whether other, potentially cleaner materials have to be identified.

This model will also be used to aid the procurement of the cryostat (P0.2), a commercial product which – within some constraints – can be custom-designed by the manufacturers (e.g., by using selected, radiopure construction materials). In collaboration with P1, it will be studied whether it is beneficial to have some copper shielding at mK temperatures directly around the target (as realized in [38]) to reduce the background contribution from the detector and the cryostat.

Towards the end of the funding period the model developed for DELight phase-I will be adapted to a preliminary design of the larger detector for phase-II, which requires a reduced background level. This renders the radioactivity level of the cryostat even more crucial as it will most likely be installed inside the massive shield (see P3.3).

P3.2: Depth requirements for underground laboratory

While the initial commissioning of DELight, the study of its response, and possibly even a first science run will be done above ground, in the surface laboratory at UHD, it is planned to move the detector to an underground laboratory of at least moderate depth for the later science runs and certainly for phase-II. This will reduce both, the muon induced neutron rate as well as associated electronic recoil backgrounds (see preliminary results in Fig. 3.1, right). The detailed detector model developed in P3.1 will be used to accurately predict the background for different laboratory options, e.g., the Vue-des-Alpes laboratory accessible via the Freiburg group, and to inform the decision where to install DELight.

The study will use either measured muon spectra (energy as well as angular distribution) from the laboratories provided by, e.g., P4, or will simulate the propagation of muons through the rock overburden with available codes (e.g., [39]) to obtain the relevant input spectra. The production of muon-induced particle showers in the laboratory walls and the detector itself, leading to secondary particles that might contribute to the ER and NR backgrounds in the dark matter search region, will be simulated using Geant4, as will the interaction of these particles in the detector and the shield. The depth requirements are defined such that the cosmogenic background contribution is negligible compared to the other background sources.

In the second half of the project, the requirements for the underground laboratory for DELight phase-II will be studied.

P3.3: Design and study of massive shield

The preliminary results shown in Fig. 3.1, where only the cosmogenic ER background induced by muons is presented and any radiogenic ER background originating from the radioactivity of the rock/concrete of the laboratory environment is not yet considered, suggest that a shield around DELight will be required. This task will study the potential of different shielding options with the Geant4 model developed in P3.1, using measured or simulated muon and gamma background spectra as input (from P4).

The required shielding could possibly be provided by a compact, massive shield made of lead and/or copper (to shield gamma rays) in combination with a layer of high-density polyethylene (to moderate and absorb neutrons). The advantage of such a massive shield is that it can be easily and quickly opened (similar to the shield of GeMSE shown in Fig. 3.2 or, e.g., the shield of the XENON100 experiment [22]), which is considered important at this stage of the project. However, water shield options will also be examined. The study will also inform about the required radiopurity level of the innermost shielding layers such that the shield does not contribute significantly to the overall background level of the instrument: In case it turns out that, e.g., standard lead is not clean enough, the radiation emitted by this shielding structure could be absorbed by an additional layer of high-purity copper or low-background lead.

Depending on the preferred underground location (P3.2), the requirements for additional muon veto detectors will be studied: for the science goal of DELight, a veto made of plastic scintillator panels should be sufficient. Such detector has the ability to detect muons with a very high efficiency, while the detection efficiency of muon-induced showers, produced by muons interacting with the laboratory itself, will be quite low.

The study will take into account the (cylindrical) shape of commercial cryostat and will develop a shield that ensures that direct line-of-sight for gammas and neutrons from the environment is blocked. It will take into account whether a Cu shielding layer at mK temperature inside the cryostat can be realized (see P3.1). The shield should not only reduce the background: while LHe has a high impedance to vibration noise from the environment it is still important to reduce vibrational background as much as possible. This also holds for electromagnetic noise which is important to achieve the design thresholds. A massive, hermetic shield around DELight should help in both aspects.

While the mechanical design of the shield is beyond the scope of P3 (see P4), it will be important to make use of the mechanical engineering expertise available in Freiburg and Karlsruhe already in this simulation phase to ensure that the proposed shield also can be constructed. The shield will be designed such that it will also be sufficient to achieve the background levels required for phase-II or that it can be upgraded in a straightforward manner.

P3.4: Material selection campaign

All materials and components close to the LHe target need to be examined for their intrinsic radioactive contamination. This is important for two reasons:

1. The use of radioactive materials or components will increase the background level which should be – if possible – avoided by replacing the part by a cleaner option.
2. While it is not always possible to replace a (often commercial) components, it is important to know the radioactive contamination of all relevant parts of the experiment in order to be able to accurately predict and understand the background, a crucial input for the dark matter search.

The prime method to non-destructively measure the radioactive contamination of materials and components is gamma spectrometry. While this method is very good to detect common anthropogenic gamma sources such as ^{60}Co or ^{137}Cs, as well as the long-lived ^{40}K, it is mainly sensitive to the later parts of the ^{238}U and ^{232}Th chains which differs from the activity in the early parts if secular equilibrium is broken. The precise knowledge of the early parts of the primordial decay chains is important to accurately predict the neutron background of the experiment as neutrons often originate from (α, n)-reactions in materials, where the α-particles can stem from the entire decay chain. The early parts can be directly addressed using, e.g., inductively coupled plasma mass spectrometry (ICP-MS), which requires a small sample from the material to be examined. And alternative material screening method, albeit not suitable for every material and also destructive, is neutron activation analysis (NAA). An advantage of the latter two methods is that they deliver results much faster than gamma spectrometry, where typical measurement times are three to six weeks, depending on the contamination and mass of the sample. In case no signal above background is observed in a measurement, upper limits on the contamination will be set such that the component can also be considered in the simulation and the background model (P3.1).

For gamma spectrometry, we will rely on our own low-background gamma spectrometer GeMSE [31, 32]. This instrument is operated and maintained by the Freiburg group and fully available for DELight. Its large sample cavity of $24 \times 24 \times 35\,\mathrm{cm}^3$ allows for the direct measurements of many of the components to be used in the final experiment (e.g., sensors, cables, connectors, feedthroughs). Samples of raw construction materials, e.g., copper or aluminum, will be procured from distributors while blocking sufficient material from the same batch for a future purchase in case the sample is found to be sufficiently clean.

Gamma spectrometry can also quantify the level of activity in the early part of the decay chains if the overall radioactive contamination level is sufficiently high. If this is not the case and an assessment of the early part is still required, we will get samples measured by means of ICP-MS at LNGS (Italy), to which we have well-established connections. In the past we have not relied on NAA for material selection, but we have already contacts to colleagues who can offer NAA (at PSI (Switzerland), Mainz and Dresden).

The emanation of radon from detector walls, which leads to a dominating background in liquid xenon-based dark matter detectors which currently lead the field for high mass dark matter searches, will likely not be relevant for DELight as radon atoms will freeze-out at the detector walls. If, however, it turns out during the project that the selection of low-Rn-emitting materials is required, this can be done with the MonXe radon emanation detector located in Freiburg [36]. This detector electrostatically collects Rn atoms emanated in a large sample chamber ($20\,\ell$) onto a PIN-diode which allows the identification of the α-decays of the Rn-daughters. Its detection sensitivity is $59\,\mu$Bq (at 90% C.L.).

P0.1-6: Procurement of cryostat, detector characterization, first science data, DELight publications, R&D towards phase-II

The work packages P0.1-6 have no leading project but are equitably performed by all participants of the RU. They are an expression of collaboration within the entire RU and thrive on the strong synergies between the projects. The activities of the RU during phase-I of DELight are framed by two main publications, a sensitivity paper (P0.1) at the beginning of the funding period and the publication of the first science results (P0.5) at the end of the funding period. These publications require input from all projects and expertise from all members of the RU and will help shape the science output of DELight. Several additional publications are planned to be published within the funding period. The cryostat is part of the coordination project and its procurement (P0.2) will be carried out by the RU together, just like the characterization of the whole DELight detector (P0.3) and the DELight operations and monitoring of the data taking during the first science run (P0.4). In parallel to phase-I, the RU will jointly start R&D towards phase-II (P0.6).

P3 will contribute to all these topics; the R&D efforts towards phase-II were already mentioned above. Regarding the detector characterization, P3 is particularly interested to study the ER rejection power of the DELight detector using the early (above ground) data, as this has a direct impact on the achievable background level. For the analysis of the science data, P3 will develop background models based on its detailed detector simulations; these models are crucial inputs for the dark matter inference.

2.4 Handling of research data

The same text applies as in Sec. 2.3 of the "Overall Description of the Research Unit and the Coordination Proposal".

2.5 Relevance of sex, gender and/or diversity

Sex and/or gender is not relevant to the research project. Though we strive for a diverse group of researchers, the level of diversity is also not relevant to the research project.

3 Project- and subject-related list of publications

[1] B. von Krosigk *et al.*, "DELight: A Direct search Experiment for Light dark matter with superfluid helium," *SciPost Phys. Proc.*, vol. 12, p. 016, 2023. doi: 10.21468/SciPostPhysProc.12.016

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4 Supplementary information on the research context

4.1 Ethical and/or legal aspects of the project

4.1.1 General ethical aspects

We do not anticipate any risks and/or harm to individuals or groups or the environment and/or the potential for other negative effects that might be posed by our research.

4.2 Employment status information

Last name: Schumann
First name: Marc
Employment status: Full professor (W3) at the University of Freiburg

4.3 First-time proposal data – Does not apply.

4.4 Composition of the project group

The composition of the group working on project P3 is summarized in the Table. The participants bring the following expertise to the project: all members are experts in the search for dark matter with low-background detectors. K. Eitel, S. Lindemann and M. Schumann developed key components for several low-background detectors, including shielding structures, and they have ample experience with simulation studies. The suite of low-background instruments available in Freiburg was developed and is continuously optimized by S. Lindemann and M. Schumann. A non-permanent postdoctoral researcher at Freiburg (A. Brown) will assist us in operating the GeMSE spectrometer.

Name and academic title	Employment status	Institution	Type of funding
Paid by institution			
Dr. Klaus Eitel	Staff scientist	KIT	institutional
Dr. Sebastian Lindemann	Staff scientist	UFR	institutional
Prof. Dr. Marc Schumann	Full professor (W3)	UFR	institutional
Dr. Adam Brown	Post-doctoral researcher	UFR	institutional
Paid by third-party			
–	–	–	–

4.5 Researchers in Germany with whom you have agreed to cooperate on this project – Does not apply.

4.6 Researchers abroad with whom you have agreed to cooperate on this project – Does not apply.

4.7 Researchers with whom you have collaborated scientifically within the past three years

All respective researchers are included in Sec. 5.7 of the overall description.

4.8 Project-relevant cooperation with commercial enterprises – Does not apply.

4.9 Project-relevant participation in commercial enterprises – Does not apply.

4.10 Scientific equipment

GeMSE low-background gamma-screening facility. The facility is used to identify radiopure materials for the construction of low-background detectors for rare event searches, e.g., XENONnT and DELight. It is the first detector world-wide with a dedicated program to measure the cosmogenic activation of meteorites. GeMSE consists of a low-background high-purity p-type germanium crystal (2.0 kg), installed in a massive shield featuring a large sample cavity of 20 liters. The detector is installed in the Swiss Vue-des-Alpes underground laboratory (620 mwe, in the Jura mountains), operated fully remotely by the Freiburg group, and is constantly used for measurements. Its background in the 100-2700 keV interval is only (82 ± 1) counts/kg/day; for massive samples and long measurement times GeMSE can achieve sensitivities in the O(50) μBq/kg range.

MonXe radon emanation detector. The group operates this detector system to directly quantify the ^{222}Rn surface emanation of materials in the laboratory in Freiburg. It electrostatically collects the charged daughter isotopes, most importantly ^{214}Po and ^{218}Po, and detectes them on a silicon PIN photodiode. Its low background level results in a detection sensitivity of $\sim$60 μBq to measure the Rn surface emanation rate of materials and components. This instrument is available for the DELight material screening campaign in case it is needed.

Cleanroom. The group operates an ISO-6 cleanroom of 10 m² area, which will be fully available for this project. Accessibly via a gray room it is equipped with workspace (desk, shelves) and standard cleanroom equipment (tools, ultrasonic baths). It will be used for the material screening campaign and to prepare low-background components for DELight.

bwForCluster NEMO computing cluster. This is a high-performance computing resource with high speed interconnect (100 Gbit/s throughput), hosted at the University of Freiburg[3]. It is available for research-related computing activities in the fields Neuroscience, Elementary Particle Physics, Microsystems Engineering and Material Sciences (NEMO). It offers 900 compute nodes plus several special purpose nodes (for login, preprocessing, interactive jobs, visualization, virtual environments), as well as two separate storage systems (home directories and workspaces). It will be used to run the Geant4-based simulation of DELight.

4.11 Other submissions – Does not apply.

4.12 Other information – Does not apply.

5 Requested modules/funds

5.1 Basic Module

5.1.1 Funding for Staff

The following staff is requested for the successful completion of this project within DELight:

- **0.5 Postdoctoral Researcher for 4 yrs:** One postdoctoral researcher, ideally with previous experience in low-background methods and rare-event-searches as well as in Monte Carlo methods, will be hired for the full funding period. We plan to hire a full-time (100%) postdoctoral researcher, the other half will be funded by project P4 which will also be conducted mainly at the University of Freiburg. The duties of the postdoctoral researcher will thus be equally shared between projects P3 and P4.
  Within this project P3, the postdoctoral researcher will be responsible for the entire material screening campaign, i.e., coordinate the procurement of material samples or commercial detector components (in coordination with P1, P2 and P4), organize their assessment with the relevant instruments, preparation of samples, operation of and analysis of data from the GeMSE HPGe spectrometer (with local support), data analysis from other facilities, etc. In addition, the researcher will supervise and support the doctoral researcher (see below) on the development of the Monte Carlo model, ensure that the measured radioactivities of the measured materials and commercial components are propagated into the simulation, and will contribute to the interpretation of the simulation results, in particular the design of the shield. The DFG Personnel Rates for 2023 foresee annual costs of 40,050 €/year for half of the 100% TV-L E13 position for the postdoctoral researcher, which amounts to **160,200 €** in total.

- **1 Doctoral Researcher for 4 yrs:** One doctoral student, ideally with a background in experimental (astro-)particle or nuclear physics, will be hired for the full funding period. Four years

[3] https://www.hpc.uni-freiburg.de/nemo

are an adequate duration for a doctoral degree in experimental particle physics which includes setting up a new experiment. The four years duration will enable the doctoral researcher to contribute to DELight from its very beginning up to the delivery of first science results.
The doctoral researcher will develop and maintain the detailed Monte Carlo model of DELight, that will be used to optimize its background, design the shield, and to assess the impact of the measured radioactivity level of certain construction materials. The doctoral researcher will also help with the material screening campaign.
The DFG Personnel Rates for 2023 foresee annual costs of 55,575 €/year for the 75% TV-L E13 position for the doctoral researcher, which amounts to **222,300 €** in total.

Both researchers will also contribute to the construction and installation as well as operation and commissioning/characterization of DELight. They will contribute to the sensitivity paper, data analysis and the publication of the first results.

5.1.2 Direct Project Costs

5.1.2.1 Equipment up to € 10,000, Software and Consumables

The following resources are required to conduct the project; they sum up to **45,000 €** in total:

- **Material selection campaign:** Samples of potentially suitable materials and components for DELight need to be procured and examined for their background level. It is usually unclear whether a material will meet the background requirements, i.e., alternative batches of the same material type (e.g., from different producers) need to be procured until a suitable material has been identified. Depending on the size of the final component and the analytics methods (non-destructive or destructive), the examined sample can be used to build the component or a larger amount of material from the same production batch needs to be reserved prior to the screening of the sample, which usually adds to the total cost. Sending samples to other institutes for mass spectrometry or neutron activation analysis will also require some funding. We estimate a total of 14,000 € for the campaign.

- **Operation and maintenance of HPGe spectrometer:** The GeMSE facility is currently fully operational. However, some of its components are rather old and prone to fail (in particular the muon veto electronics: HV supplies, NIM modules) or continuously wear out (liquid nitrogen dewars that are regularly moved to Bern for refills, automated cryogenic valves) such that 12,000 € for replacement components/detector maintenance are required to ensure the availability of the facility over the full duration of the project.

- **Detector cleaning campaign:** Especially the components in contact or close to the LHe target need to be cleaned to remove surface contaminations. The exact cleaning procedure depends on the specific material but often includes electropolishing and/or surface treatment with acids, combined with surface cleaning – usually in an ultrasonic bath – with special cleaning detergents (e.g., ELMA) and/or ethanol, acetone, DI water etc. Depending on the size of the component, acid-resistant vessels or ultrasonic baths need to be procured. We estimate total costs of 11,000 €.

- **Cleanroom consumables:** The samples for the material selection campaign as well as the final detector components need to be prepared in a cleanroom environment. This requires standard cleanroom consumables such as gloves, overalls, hair covers, shoes, ultra-pure ethanol, DI water, sticky mats, precision wipes and replacement pre-filters for the HEPA filter fan units (FFUs). Total costs: 8,000 €.

5.1.2.2 Travel Expenses

For DELight Project 3 a total of **32,600 €** travels funds are required to cover the following costs:

- **International conferences.** The attendance of and contribution to relevant international conferences, like IDM (the International Conference on the Identification of Dark Matter), LDW (Meeting of the Light Dark World International Forum), TAUP (the International Conference on Topics in Astroparticle and Underground Physics), LTD (the International Workshop on Low-Temperature Detectors) or LIDINE (LIght Detection In Noble Elements), provides important visibility, networking, and interpersonal communication opportunities strengthening DELight and the careers of its scientists. We estimate the cost for a typical 5 day long international conference or workshop at 1500 € and foresee travels to 4.5 conferences in the 4 years funding period (0.5 trips indicate that the other half is funded by DELight Project 4). The total amount required is thus **6800 €**.
- **DPG Spring Meetings.** Doctoral and postdoctoral researchers, as well as the DELight project which they represent, strongly benefit from attending the annual Spring Meeting of the DPG (German Physical Society) every year. Especially doctoral researchers use this opportunity for their first presentations to the wider scientific community. We estimate the costs for a 5 day long trip to the DPG Spring Meeting at a Germany city at 1000 € and plan with six trips during the funding period, which amounts to **6000 €**.
- **DELight in-person meetings.** This project is tightly connected to all other DELight projects (e.g., P1 – cryogenic setup and ^{4}He cell, P2 – MMC detectors, P4 – Site and infrastructure, P6 – Science analysis), which requires close coordination with our colleagues. This requires occasional travel to the other institutions for day-long in-person meetings. Here we can clearly benefit from the close geographical proximity of the three DELight institutions. We estimate the average costs for a short trip at 150 € and anticipate four short trips per year. This amounts to **2400 €** in total. (The costs for traveling to or hosting the two in-person collaboration meetings per year are covered by the Coordination Project.)
- **Installation shifts.** The installation of the DELight detector is a collaborative effort involving the entire RU. This includes construction and installation of hardware which requires coordinated work over multiple days in the form of installation shifts. While members of the groups at KIT and UHD can commute daily between Heidelberg and Karlsruhe, the same is not true for members of the groups at Freiburg. In this case, funding for extended stays at the partner institutions is required. A typical length of a shift is 7 days with an estimated cost of 1100 €. We anticipate that one shift per person funded via the RU and one externally funded member of the RU is required in year 1 and two shifts in years 2-3. Thus 2.5 people will each take five shifts in total, adding up to **13,800 €**.

- **Trips to HPGe facility.** The UFR HPGe spectrometer GeMSE is located in the Vue-des-Alpes road tunnel in Switzerland. It can be reached by car in about one hour from Bern (65 km) or in about 2.5 h from Freiburg (200 km). Regular trips to the tunnel are required to operate the detector (refilling of liquid nitrogen reservoirs), to change samples and for detector maintenance. For this project we estimate typically six trips/year, taking into account that also the colleagues from project P4 will regularly travel to Vue-des-Alpes where they can take over our local tasks. The cost of a single trip depends on the means of transportation (train, car, train discount card, number of people traveling); based on previous experience it is in average 150 € per person and trip. The total cost foreseen is thus **3600 EUR** in total.

5.1.2.3 Visiting Researchers (excluding Mercator Fellows)

Does not apply. In case short term visits of external researchers become necessary, their visits will be supported by the applicant's institutional funds or via long-term fellowships[4] offered by the Freiburg Institute for Advanced Studies (FRIAS) of the University of Freiburg.

5.1.2.4 Other Costs – Does not apply.

5.1.2.5 Project-related Publication Expenses

Does not apply. Project-related publications will be published in journals of the Sponsoring Consortium for Open Access Publishing in Particle Physics (SCOAP^3) where no extra costs occur. In addition, all articles will be posted on the open-access `arXiv` preprint server.

5.1.3 Instrumentation

No investment in equipment exceeding 10,000 € or major instrumentation is required as the scientific equipment for the project already exist, see Section 4.10.

5.1.3.1 Equipment exceeding € 10,000 – Does not apply.

5.1.3.2 Major Instrumentation exceeding € 50,000 – Does not apply.

[4] https://www.frias.uni-freiburg.de/en/funding-programmes/frias-fellowships

P4 - Site and infrastructure

Applicant: Sebastian Lindemann (Freiburg)
Co-applicants: Klaus Eitel (Karlsruhe), Christian Enss (Heidelberg), Marc Schumann (Freiburg)

Project Description

DELight is a new particle physics experiment that can only be realized through the confluence of all six projects. Each project plays a fundamental and unique role, where the project described in the following is responsible for **selecting the proper site for the experiment, managing the necessary infrastructure, including the mechanical realization of the experiment's shield, and monitoring and controlling all system-relevant parameters.**

If dark matter exists in the form of LDM, its interaction with ordinary matter is extremely weak. Consequently, the expected number of signal events induced by LDM scattering off DELight's superfluid helium target is, at best, quite small. To detect these LDM-induced signals, it's crucial to thoroughly characterize and, whenever possible, prevent interference from similar signals originating from standard physics processes. DELight will implement mitigation measures to avoid and, when not possible, discriminate against such background events at various stages of the experiment. Among these measures are particle identification techniques that exploit differences in micro-physics to distinguish between signal and background (see P6 for more details). The use of radiopure construction materials (see P3) exemplifies one aspect of background avoidance. This effort will be complemented by proper shielding for the experiment (P3 and P4). (Deep) underground laboratories, due to their substantial rock overburden, excel at shielding against the hadronic component of cosmic rays and significantly reducing the muon flux at the experimental site. Gamma radiation, mainly originating from the surrounding rock and concrete, can be efficiently mitigated through the installation of a massive shield made of radiopure high-Z materials. This project will contribute to the design and will lead the technical realization of the shield for DELight.

Operating DELight containing several liters of superfluid helium, potentially in a remote location, presents significant challenges that must be addressed. Safe management of the experiment's helium inventory necessitates a comprehensive risk analysis, including solutions for quickly venting the detector in case of emergencies to prevent any safety hazards to personnel or equipment. Access to live detector performance data is crucial to promptly respond to unforeseen events, such as equipment failures or power outages. Within this project we will develop a system to continuously monitor the various detector systems, with the capability to control them when necessary.

1 Starting Point

State of the art and preliminary work

Underground facilities. Neutrinos and the search for dark matter are driving forces in experimental physics, combining nuclear, particle, and astroparticle physics, and cosmology. These studies exclusively occur in underground laboratories, where they are shielded from cosmic rays. Detecting dark matter particles and rare electroweak decays presents challenges due to their extremely low counting rates and the presence of significant background noise from radioactive decays and cosmic rays. To mitigate the impact of cosmic radiation, detectors must be shielded by going underground. Various deep underground facilities exist (see e.g., [1–5]) featuring rich science beyond neutrinos and dark matter search: The demand for ultra-low radioactive materials in underground experiments for dark matter and neutrinos spurred research into highly sensitive detectors capable of measuring minuscule radiation levels [6–10]. These detectors, sensitive to radiation levels one millionth that of the human body's natural radiation, must be situated as well underground to shield them from cosmic radiation. The study of endolithic bacteria and bio-leaching technologies is gaining continuous interest [11–13]. New concepts in underground biology explore the influence of radiation (or its absence) on evolutionary processes and the formation of bio-aerosols.

Cryogenic liquid-gas detectors searching for DM, neutrinos and rare decays, both within the SM and beyond, are successfully operated in deep underground laboratories since decades [14–17]. Depending on the accessibility of the underground laboratory, it is advantageous to assemble and commission the experiment first above ground before relocating it underground. For example, the detector of the Large Underground Xenon (LUX) experiment was commissioned overground at SURF for an initial six-month run, allowing for a proper commissioning of the system [18]. The assembled detector was afterwards transported underground from the surface laboratory in an effort lasting a few days only. Similarly, its successor experiment, LZ, was assembled in three stages – off-site subassembly, surface assembly, and underground assembly. The general strategy was to do as much work as practical off site at universities and national laboratories, where highly skilled, specialized labor can easily work with students and scientists. This reduced travel costs and the parts delivered to the site were tested, clean, and ready to use [19].

For phase-I of DELight we plan to follow a similar approach. Detector concepts will be tested at Karlsruhe (P2) and Heidelberg (P1), where phase-I of DELight is supposed to be commissioned and collect first science data. If it proves beneficial already during phase-I, DELight will be relocated to an underground laboratory; otherwise, the relocation will take place during phase-II.

Many science- and safety-relevant aspects of handling the various (cryogenic) liquids have been solved over the past decades. Collecting and making available slow control data of the detectors to the data analysis has turned out to be essential and is a common standard in the field as will be discussed next.

Slow data monitor and control systems. Monitoring both process and environmental data is a standard procedure in industry, science and with increasing frequency also in private homes. In modern industry live process data plays a pivotal role. It provides real-time insights into the performance of manufacturing processes, allowing for immediate adjustments to optimize efficiency, quality, and safety. In industry those systems are referred to as Supervisory Control and Data Acquisition (SCADA). SCADA is a crucial technology that empowers industries to monitor, control, and optimize complex processes and systems. SCADA systems serve as the nerve center for a wide range of critical operations, from managing power grids and water treatment plants to overseeing manufacturing lines and oil refineries. At its core, SCADA is a software and hardware solution designed to collect data from sensors and equipment located in the field. This data is then transmitted to a central computer system, where it's processed, analyzed, and presented to human operators. These operators can then make informed decisions and execute control commands remotely, ensuring the efficient and safe operation of industrial processes. Key components of a SCADA system include:

- RTUs (Remote Terminal Units) and PLCs (Programmable Logic Controllers): These are field devices responsible for collecting data and controlling equipment. RTUs and PLCs are often equipped with sensors to monitor parameters like temperature, pressure, flow, and voltage.
- Communication Infrastructure: SCADA systems rely on robust communication networks, such as radio, satellite, or cellular, to transmit data between field devices and the central control system. This ensures real-time data availability.
- SCADA Master Station: The central component of the system, the SCADA master station, includes servers and software for data processing, visualization, and control. Human-machine interfaces (HMIs) provide operators with a user-friendly view of the processes.
- Database: SCADA systems store historical data in databases, allowing for trend analysis, reporting, and auditing. This historical data is invaluable for troubleshooting, compliance, and process optimization.

SCADA is widely used in managing various sectors such as water treatment, electrical grids, oil and gas pipelines, and manufacturing. It optimizes resource allocation, reduces downtime, and responds swiftly to faults. It also plays a role in transportation systems and environmental monitoring, ensuring compliance. In commercial buildings, SCADA enhances energy efficiency and security. With advancements in IoT and cloud computing, SCADA offers greater scalability and predictive maintenance. ABB, Emerson, Siemens, and General Electric are some of the key players in the commercial SCADA market [20–23].

To distinguish between data acquisition (DAQ) systems for "fast" science data (P5), often sampling at MHz frequencies from high-speed sensors like DELight's MMCs, and SCADA systems acquiring process control data from auxiliary sensors, typically sampled at a maximum of a few Hz, in particle physics the latter sometimes is referred to as Slow Control (SC). Many of the medium-size to large experiments in particle physics run commercial, customized or home-made SC systems. While industrial SCADA systems are commonly employed in large projects [24–26], they are often impractical for considerably smaller laboratory projects due to limited scientific scope, operational duration, and available labor. Moreover, many smaller projects do not require the full complexity of SCADA systems, which manage intricate modifications of a detector's state. Open-source slow control solutions like EPICS (Argonne) [27], NOMAD (ILL) [28], or MIDAS (PSI/TRIUMF) [29] are available for larger [30, 31] to medium-sized experiments and research centers with multiple similar instruments [32]. However, these solutions can be overly complex for small R&D projects with only a few different instruments. Consequently, such projects often operate without slow control or rely on custom solutions with limited functionality [33]. To address this gap, the Doberman (Detector OBsERving and Monitoring ApplicatioN) software framework was developed by members of this RU [34]. In addition to monitoring and controlling the individual detectors comprising a particle physics experiment, having comprehensive and complete slow control data is mandatory for the detection of new physics. Any signal must undergo thorough scrutiny and should not correlate with atypical detector conditions. This need is particularly pronounced in the context of diurnal and annual dark matter rate modulation studies [35–38], which would be infeasible without consistently controlled and well-monitored detector conditions.

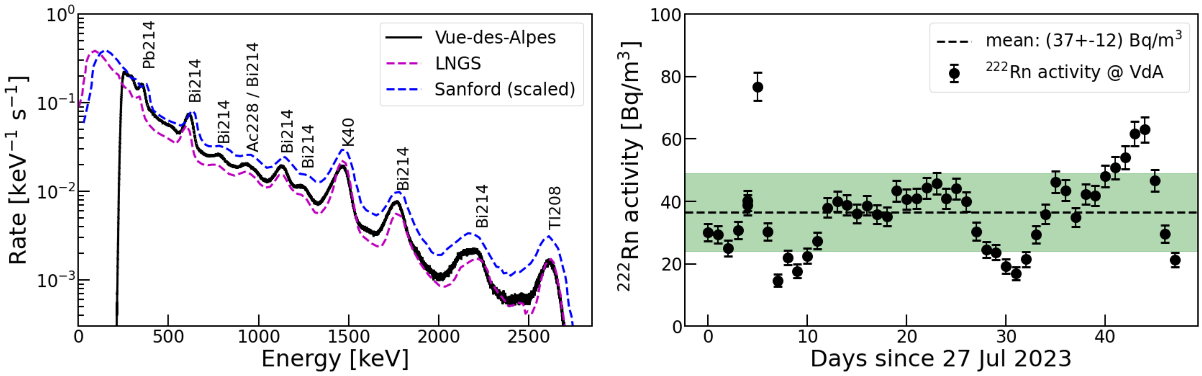

Figure 4.1: (left) Gamma spectrum normalized by time and energy measured using 3-inch NaI(Tl) scintillating crystals at the Vue-des-Alpes (VdA) laboratory (solid black line). For comparison two measurements using similar detectors at the LNGS underground laboratory (dotted magenta line) and at the Sanford underground laboratory (dotted blue line) are shown. Data for the latter two are extracted from [40] and [41], respectively. The Sanford data were collected using a 5-inch crystal. For the plot the data were re-scaled by the mass ratio to compare with the VdA and LNGS data. (right) Ambient ^{222}Radon concentration measured at the VdA laboratory using a commercial RAD7 monitor. Data collected in summer 2023.

Preliminary work. The initial detector assembly and commissioning are expected to take place within the research unit's above-ground laboratory at the Kirchhoff-Institute for Physics in Heidelberg. This choice facilitates easy access to the detector, enables prompt assistance from the institute's nearby mechanical workshops and engineers, and mitigates the logistical challenges associated with planning personnel and equipment availability in a potentially remote location. Nevertheless, achieving DELight's scientific objectives may necessitate a substantial reduction in background events induced by muons and cosmic activation. This, in turn, requires the relocation of the detector system to an underground laboratory.

The proposed research unit has the unique opportunity to host the DELight experiment in the **Vue-des-Alpes (VdA) underground laboratory** [39], which is located in the road tunnel connecting the cities of Neuchâtel and La Chaux-de-Fonds in Switzerland. The laboratory was build in 1996 purposed to host screening facilities selecting radiopure materials and is now operated by the Laboratory for High Energy Physics (LHEP) of the University of Bern. Access to the laboratory is via LHEP and is formalized via a memorandum of understanding (MOU). The laboratory is situated in the safety booth of the bidirectional 3250 m long tube of the La Vue-des-Alpes road tunnel and can be reached by car in about two hours from the closest participating institute. The laboratory is shielded by 230 meters of rocks, equivalent to 600 meters of water. This shielding reduces the cosmic neutron flux to zero and decreases the muon flux by a factor of approximately 2000 [9]. The laboratory is well-equipped with power, air ventilation, and internet access. Additionally, it provides a crane for moving heavy equipment. The laboratory features a useful surface area of 40 m^2. Presently, in one corner, the UFR group operates the low-background gamma-spectrometer GeMSE (see P3). Nevertheless, we anticipate that the available space will adequately accommodate both phases of DELight, and we will consider space limitations when designing the experiment.

A preliminary study on the laboratroy's gamma background, most likely originating from the surrounding rock and concrete, results in a comparable flux as observed at deeper laboratories [40–42] (cf. also Fig. 4.1 left), stemming mostly from ^{40}K and the uranium and thorium decay chains. Radon and its progenitors poses a threat to practically all underground neutrino and dark matter

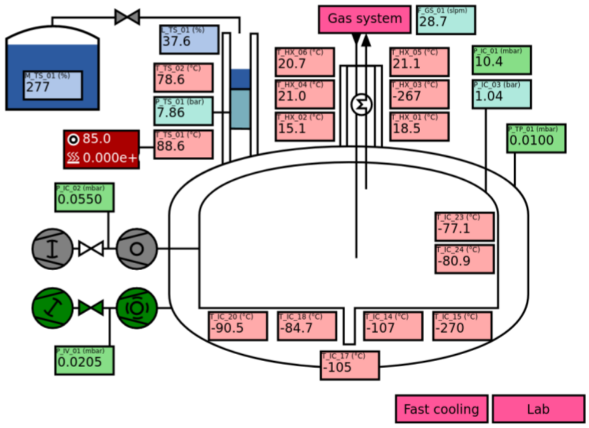

Figure 4.2: Web interface of a distributed slow control system (Doberman) deployed at UFR to monitor and control the large scale liquid Xe platform PANCAKE. The colored boxes display a subset of the latest readings of PANCAKE's various sensors. All readings are stored in a database, trends are displayed at convenience and actuators are remotely controlled.

experiments [43–45]. The laboratory air, which is part of the road tunnels ventilation system, was recently measured to contain about 40 Bq/m^3 of radon - again due to trace contamination of the uranium chain in the rock and concrete (cf. Fig. 4.1 right). Preliminary studies on the vibrational noise induced by vehicles in the road tunnel, conducted during two phases – normal traffic and tunnel maintenance with traffic closure – indicate that the VdA laboratory's environmental conditions are not inferior to those of surface laboratories.

Despite their large spread in industry, commercial SCADA software can present drawbacks when applied in scientific contexts. One of the most notable issues is their expense, as they typically involve substantial initial purchase costs and may also require ongoing monthly or yearly fees. Additionally, these systems are often designed to function with proprietary hardware components from the same manufacturer, imposing limitations and driving up expenses.

S. Lindemann and M. Schumann are responsible for the operation of liquid xenon and germanium detectors. They have developed and continuously advanced the **open-source slow control system Doberman** designed for these instruments [34, 46], which can be easily adapted for use in other experiments. Doberman is a lightweight SCADA software suite developed in Python, offering a smaller subset of features and connectivity when compared to commercial systems. In this system, the roles of RTUs and PLCs are typically fulfilled by small-scale Linux-based computers equipped with dedicated analog and digital I/O modules. In recent years, Kunbus' modular and inexpensive industrial PC [47] based on the well-known Raspberry Pi, that can be seamlessly expanded by a variety of suitable I/O modules, has demonstrated excellent performance. Configuration data are stored and accessed using the open-source database MongoDB [48], while historical data are managed using the open-source database InfluxDB [49]. Communication between devices is facilitated through the primary Doberman instance, usually installed on a server-grade Linux-powered PC. Field bus communication is currently not supported to streamline the system and minimize added complexity. Over the past few years, this slow control system has been successfully adapted for two liquid xenon test platforms [50] conducted in the laboratory at UFR, the GeMSE gamma screening facility (see below and also P3) and, recently, for test beam campaigns in the context of SHiP, a proposed beam dump experiment at CERN designed to search for any type of very weakly interacting long-lived particles [51]. The larger of the two liquid xenon experiments, PANCAKE, has the capacity to hold more than 400 kg of xenon in liquid form. Given the high cost of xenon gas, it is imperative to operate the system with minimal losses. This goal presented numerous technical challenges that required resolution. At the core of addressing these challenges lay the need for a reliable monitoring and control software system, a solution successfully provided by Doberman. As an illustration, Figure 4.2 showcases the interactive web-based control panel for PANCAKE's primary detector instrumentation display.

The low-background HPGe γ-spectrometer GeMSE [52] is operated remotely at the Vue-des-Alpes underground laboratory, employing a derivative of the same slow control and monitoring system. This spectrometer successfully operates within a high-Z material shield, similar to the design envisioned for DELight. To facilitate the placement of samples into the GeMSE spectrometer, a portion of the shield must be temporarily removed to provide access to the sample cavity adjacent to the germanium crystal. GeMSE's shield has been constructed with heavy-load rails, housed within a boil-off nitrogen-purged glovebox for radon reduction. This setup allows for swift sample exchanges, typically accomplished within a matter of minutes [9].

2 Objectives and work programme

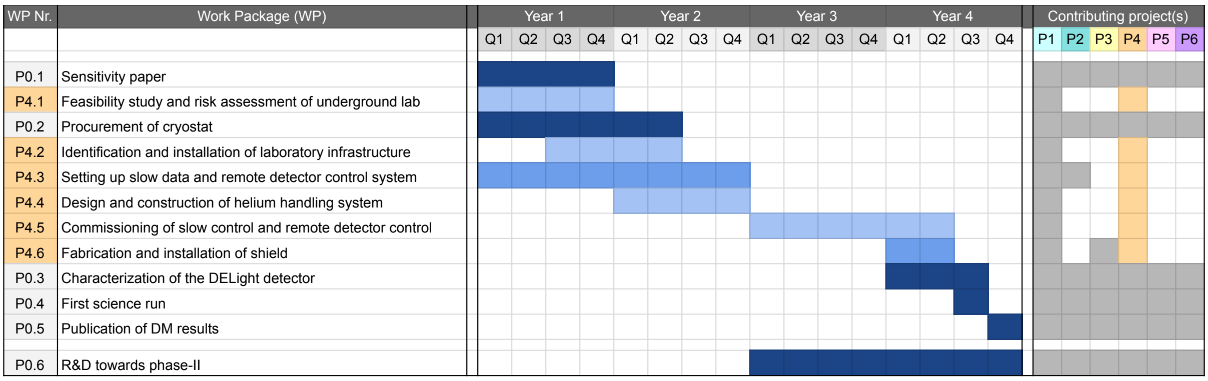

Figure 4.3: Summary of the P4 work programme. The work package (WP) numbers indicate the respective lead project (here P4) and the count within that project's list of WPs. The P0 identifier is used for WPs that are equitably performed by all participants of the RU. The shades of blue within the timeline indicate the amount of contributing projects. The lightest blue is used for WPs only conducted within P4 and one second project. The darkest blue is used for WPs to which all projects P1 - P6 contribute. The rightmost block of the program signals the lead project (color) and the further contributing projects (gray).

2.1 Anticipated total duration of the project

The total duration of this project is fully aligned with the timeline of DELight phase-I as described in Sec. 2.2 of the "Overall Description of the Research Unit and the Coordination Proposal". The anticipated total duration of the project is four years.

2.2 Objectives

Within the framework of P4, one major objective is the construction of the shield for DELight. This project will work in close collaboration with P3 to thoroughly evaluate the mechanical feasibility and the potential influence on the physics sensitivity of various shield designs. The shield's design must be adaptable to the commercial dilution cryostat that houses the superfluid helium cell, a task led by P1, as well as the MMC-based wafer calorimeters, as managed by P2. Furthermore, the shield should be easily adaptable to accommodate various potential locations currently under consideration. The second major objective will be to develop a Doberman-based slow control system, tailored to the specific needs of DELight. This system will be responsible for monitoring and, when necessary, controlling essential operational parameters. Additionally, a slow data storage and management scheme will be collaboratively developed with P5. This effort aims to harmonize slow control and scientific data (see Fig. 5.1 in the P5 description), enabling the comprehensive utilization of slow data information during the subsequent scientific analysis as outlined in P6. The third major objective is to identify and establish the necessary laboratory infrastructure in collaboration with P1 and P2. The primary emphasis will be placed on establishing the infrastructure required for the safe handling of the detector's helium. The DELight detector will be initially assembled within the laboratory at UHD, where the first sets of scientific data may be collected. As the sensitivity to LDM particles increases, the shielding provided by the rock overburden in an underground laboratory will become progressively more crucial. The fourth major objective of this project is to investigate the feasibility of operating the DELight detector at the VdA underground laboratory. Additionally, preparatory work will be conducted to identify the essential infrastructure requirements for any underground laboratory setting.

2.3 Work programme including proposed research methods

Project P4 is structured in six work packages (WP), each addressing a dedicated objective stated in section 2.2. The timeline of the different WPs as well as the interplay with contributing projects are summarized in Fig. 4.3.

P4.1: Feasibility study and risk assessment of underground lab

The rock overburden of an underground laboratory, which shields the hadronic component of cosmic rays and substantially diminishes its muonic component, has the potential to greatly enhance the scientific capabilities of DELight. However, underground laboratories present distinctive challenges and considerations that must be carefully addressed. P4.1 delves into the critical factors involved in evaluating the feasibility and potential risks associated with the operation of DELight in an underground laborartory. Given the unique availability of the Vue-des-Alpes laboratory, the primary focus of P4.1 will be directed toward this specific location.

Space Constraints for DELight: One of the primary considerations is the availability of adequate space for the experiment. Underground laboratories frequently encounter spatial constraints, necessitating careful planning for the placement of essential DELight equipment, including the central fridge, the data acquisition (DAQ) system, electronic racks, and the high-Z material gamma shield. Close cooperation with P1 (fridge), P3 (shield), and P5 (DAQ) will be instrumental in evaluating the experiment's requirements and conducting a feasibility study for the installation of DELight.

Air Exchange and Ventilation Systems: Adequate ventilation is of paramount importance in underground labs, ensuring the safety and well-being of researchers while maintaining stable environmental conditions. These ventilation systems must effectively remove pollutants, regulate temperature and humidity, and ideally, mitigate the accumulation of radon gas. Moreover, air exchange rates must be substantial enough to sustain a proper oxygen concentration in the lab, particularly in the event of an unforeseen rapid venting of DELight's helium into the laboratory air. In the case of the Vue-des-Alpes laboratory the ventilation system is part of the road tunnel's infrastructure. Exchange with the local authorities complemented by measurements of air exchange rates and monitoring of temperature, humidity and radon concentration (cf. Figure 4.1 right) will allow us to conclude on this aspect.

Ambient Radioactivity: While underground laboratories enjoy the advantage of reduced radiation levels from cosmic rays, they are not entirely exempt from radiation sources. Primarily attributed to the presence of primordial uranium and thorium series, along with the long-lived isotope ^{40}K, in the surrounding rock and concrete, ambient gamma and neutron radiation can be elevated compared to surface facilities. Therefore, it is imperative to conduct a comprehensive assessment of ambient radioactivity, including the concentration of airborne radon gas. These data are indispensable for the research unit to assess potential impacts on the overall background radiation at potential DELight sites and to implement the necessary shielding and safety measures.

Ground Vibration and Seismic Activity: Underground labs need to assess the level of ground vibration caused by both seismic and human-made activity, e.g., in the case of the Vue-des-Alpes laboratory, the nearby road tunnel. Vibration can adversely affect experiments, especially those requiring extreme precision or stability. Mitigation measures, such as shock-absorbing foundations or a seismic platform (see e.g. [53]), may be necessary to reduce the impact of vibrations.

Electric Power and Internet Connectivity: Reliable electric power and internet connectivity are fundamental prerequisites to safely operate DELight in a remote underground laboratory. Any underground facility to host DELight must ensure that it can provide a stable power supply to the sensitive instruments and maintain a robust internet connection for data transmission, control, and communication with the researchers from this RU.

P4.2: Identification and installation of laboratory infrastructure

The initial commissioning of individual components of DELight as well as of the full experiment will take place in Heidelberg and Karlsruhe, both well-equipped laboratories capable of supporting above-ground operations. This work package will closely monitor these surface operations to assess DELight's requirements and facilitate a seamless transition to an underground laboratory. Following the feasibility study and risk assessment in P4.1, the identification and installation of necessary laboratory infrastructure for DELight's underground deployment will be executed. This includes the potential installation and distribution of electric power, adequate illumination, and network connectivity on-site. Moreover, safety-critical systems, such as oxygen sensors, fire detectors, and extinguishers, will undergo evaluation to ensure they align with DELight's operational needs. Modifications will be made as deemed necessary. The inclusion of a seismic platform, e.g. akin to SuperCDMS [53], is not part of the phase-I plan for DELight. Nevertheless, if the data collected during this first phase indicate potential advantages derived from the incorporation of such a device, the laboratory for phase-II of the project could be furnished with such equipment.

P4.3: Setting up slow data and remote detector control system

A slow data storage and handling scheme will be developed in collaboration with P5 harmonizing slow control and science data (see Fig. 5.1 in the P5 description). As an example, a conditions database developed in P5 will access pertinent sensor data collected by the slow control system as needed. This data may be used for run control decisions or to correlate information with the scientific data. This will allow to fully exploit slow data information during the science analysis (P6). The slow control and monitoring system for DELight will be built upon the foundation of the open source project Doberman [34], developed and maintained by researchers of this RU. In its current version, Doberman harmonizes the merits of Python code, known for its readability and ease of programming, with the well-established industry-standard time series database, InfluxDB, which is also open-source. To establish robust data management, a dedicated Linux-based slow control server will be installed. This server will serve as the host for the primary instance of Doberman and will manage the local InfluxDB instance that houses DELight's slow control data. In addition to this, a remote instance of InfluxDB will be set up to ensure the existence of a secondary, redundant copy of the data, offering an added layer of data security and availability. Doberman further supports the operation on distributed systems. This configuration has proven very useful in the context of the liquid xenon test facility Pancake. In this set-up the primary instance on the slow control server manages additional Doberman instances running on the same network. This solution showed it's particular strength in combination with the industry-grade and open source Revolution Pi (from Kunbus) modules, which host at their core a Raspberry Pi computer running a full Linux operation system, that can be extended by a variety of analog and digital in- and output modules some of which also supporting common industrial network protocols. In the terminology introduced earlier, these modules assume the functions of RTUs and PLCs.

The selection of appropriate sensors crucial for data collection within the experiment and its associated infrastructure will be a collaborative effort involving P1 (LHe cell), P2 (MMCs), P4 (slow control) and P5 (DAQ). The objective is to find an optimal balance between sensor specifications and their seamless integration into the slow control and monitor system. These sensors encompass a broad spectrum, ranging from environmental monitors, where project responsibility lies within this project (P4.2), to specialized scientific instruments. Close collaboration with the hardware-focused projects P1 and P2 is imperative to achieve precise interfacing with the control system. The system's design should be forward-thinking, allowing seamless integration of future sensor additions or upgrades, thereby ensuring scalability. Additionally, remote access and control capabilities should be implemented securely, allowing operators to monitor and adjust sensors remotely. This enhances the system's flexibility and enables real-time responses to changing conditions.

P4.4: Design and construction of helium handling system

Our plan involves utilizing commercially available helium, which is supplied and distributed by dedicated companies in pressurized gas cylinders. Within this work package, our objective is to design and construct a system that ensures the clean connection of new helium gas cylinders by means of purge lines and pump ports. Additionally, we will implement monitoring procedures for their contents, likely employing gas pressure and weight measurements. Furthermore, we will establish regulation and monitoring mechanisms for the outlet pressure, aligning it with the requirements of DELight's helium filling system to be developed as part of P1.

At the end of each cool-down cycle during phase-I of DELight, we do not intent to collect the helium but rather vent it in a safe way. This is expected to be much more cost-effective than the installation of a recuperation system e.g., based on clean compressors. However, we plan to investigate on such solutions for phase-II of DELight already during the first funding period.

P4.5: Commissioning of slow data and remote detector control

Once the slow data and remote detector control system is set up (P4.3) and the first sensors of the various subsystems are in place, rigorous testing of the software controlling these sensors can start. Extensive testing, also including simulated scenarios and real-world conditions, is vital to identify and rectify potential issues, ensuring data accuracy and system stability.

One important aspect at this stage is proper alarm management. In modern control rooms, operators are often faced with an overwhelming number of alarms due to the low cost of alarm configuration in current generation SCADA systems. This inundation of alarms makes it difficult for operators to prioritise their actions, even during normal operations. Working closely with the cryogenic experts from P1 and P2, we will identify an alarming scheme that will allow DELight to operate safely and stably, avoiding alarm flooding.

P4.6: Fabrication and installation of shield

In this work package we will collaborate closely with P3 to develop a high-Z material shield for the purpose of shielding against ambient gamma rays. This shield may also be augmented by incorporating layers of high-density polyethylene or water to mitigate the impact of neutrons. Additionally, muon veto detectors might be integrated into the design, depending on the findings of the Geant4 model established in P3. The primary emphasis of this work package is on the mechanical realization of this shield within the constraints posed by the laboratory and the specific requirements of the experiment. The shield has to fit within the available space and should allow for accessing the relevant parts of the helium cell for maintenance and upgrades. We envision a shield similar to the one used by GeMSE ([9] or cf. Figure 3.2) or the XENON100 experiment [16].

P0.1-6: Procurement of cryostat, detector characterization, first science data, DELight publications, R&D towards phase-II

The work packages P0.1-6 have no leading project but are equitably performed by all participants of the RU. They are an expression of collaboration within the entire RU and thrive on the strong synergies between the projects. The activities of the RU during phase-I of DELight are framed by two main publications, a sensitivity paper (P0.1) at the beginning of the funding period and the publication of the first science results (P0.5) at the end of the funding period. These publications require input from all projects and expertise from all members of the RU and will help shape the science output of DELight. Several additional publications are planned to be published within the funding period. The cryostat is part of the coordination project and its procurement (P0.2) will be carried out by the RU together, just like the characterization of the whole DELight detector (P0.3) and the DELight operations and monitoring of the data taking during the first science run (P0.4). In parallel to phase-I, the RU will jointly start R&D towards phase-II (P0.6). A few key contributions of P4 will be highlighted in the following.

Project P4 will closely follow the procurement and surface commissioning of the cryostat in order to draw the necessary conclusions for the laboratory requirements of a subsequent installation in an underground laboratory. Further P4 will participate in the data analysis process, with a specific emphasis on assessing the slow control data obtained from DELight's auxiliary sensors. The primary goal is to establish criteria for data selection based on detector stability considerations. Additionally, the project will center its efforts on conducting diurnal rate modulation studies, which could potentially serve as compelling evidence for dark matter existence if the stability of detector conditions can be demonstrated.

2.4 Handling of research data

The same text applies as in Sec. 2.3 of the "Overall Description of the Research Unit and the Coordination Proposal".

2.5 Relevance of sex, gender and/or diversity

Sex and/or gender is not relevant to the research project. Though we strive for a diverse group of researchers, the level of diversity is also not relevant to the research project.

3 Project- and subject-related list of publications

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4 Supplementary information on the research context

4.1 Ethical and/or legal aspects of the project

4.1.1 General ethical aspects

We do not anticipate any risks and/or harm to individuals or groups or the environment and/or the potential for other negative effects that might be posed by our research.

4.2 Employment status information

Last name: Lindemann
First name: Sebastian
Employment status: Currently holding a fixed-term researcher position (E13). The promotion to a permanent institutional scientific position (E14) at the University of Freiburg is currently ongoing. The process will be completed at the anticipated start date of the RU.

4.3 First-time proposal data

This is a first-time proposal of Sebastian Lindemann.

4.4 Composition of the project group

Table 4.1: Individuals who will work on the project but will not be paid out of the project funds.

Name and academic title	Employment status	Institution	Type of funding
Paid by institution			
Dr. Klaus Eitel	Staff scientist	KIT	institutional
Prof. Dr. Christian Enss	Full professor (C4)	UHD	institutional
Dr. Sebastian Lindemann	Staff scientist	UFR	institutional
MSc Santiago Ochoa	Staff engineer	UFR	institutional
Claudio Schmidt	Staff technician	UFR	institutional
Prof. Dr. Marc Schumann	Full professor (W3)	UFR	institutional

The composition of the group working on project P4 is summarized in Tab. 4.1. The participants bring the following expertise to the project. S. Lindemann and M. Schumann have significant expertise in safely operating large quantities of cryogenic noble gases (N_2, Ar, and Xe). In this context they develope and maintain the distributed slow control system Doberman. C. Enss possesses substantial expertise in the operation of cryogenic detectors, including those utilizing liquid and superfluid helium. This experience is instrumental in establishing the protocols for safety measures and gas recovery systems. K. Eitel has vast experience in installing and operating cryogenic Ge detector systems surrounded by hermetic passive and active shielding at underground sites. K. Eitel brings a wealth of expertise in the installation and operation of cryogenic germanium detector systems enclosed within hermetically sealed passive and active shielding structures at underground locations. S. Ochoa is a mechanical engineer with expertise in mechanical design, 3D CAD modeling and finite element analyses. C. Schmidt is a trained precision mechanic ("Feinwerkmechanikermeister") with experience in the design, construction, and assembly of both large and small mechanical equipment.

4.5 Researchers in Germany with whom you have agreed to cooperate on this project – Does not apply.

4.6 Researchers abroad with whom you have agreed to cooperate on this project – Does not apply.

4.7 Researchers with whom you have collaborated scientifically within the past three years

All respective researchers are included in Sec. 5.7 of the overall description.

4.8 Project-relevant cooperation with commercial enterprises – Does not apply.

4.9 Project-relevant participation in commercial enterprises – Does not apply.

4.10 Scientific equipment

Cleanroom. The group operates an ISO-6 cleanroom of $10\,\mathrm{m}^2$ area, which will be fully available for this project. Accessibly via a gray room it is equipped with workspace (desk, shelves) and standard cleanroom equipment (tools, ultrasonic baths). It will be used to prepare low-background components for DELight and will prove very useful to prepare, clean and bag for transport the inner-most parts of the shield.

Mechanical and electrical workshop. The physics department of the UFR is hosting both a mechanical and an electrical workshop, along with their respective staff. The mechanical workshop is well-equipped, featuring large 5-axis mills, CNC lathes, and various smaller machines capable of processing metal, plastics, and even wood. Additionally, a new laser cutter for metals and plastics is currently being acquired. The RU has access to the machine shop and its highly skilled personnel, which will be extremely advantageous when constructing the shield.

Vue-des-Alpes underground laboratory. The Vue-des-Alpes laboratory is situated in the road tunnel connecting the cities Neuchâtel and La Chaux-de-Fonds in Switzerland. It was build in 1996 purposed to host screening facilities selecting radiopure materials [39]. Access to the laboratory is via the Laboratory for High Energy Physics (LHEP) of the University of Bern. The laboratory is shielded by 230 meters of rocks reducing the cosmic neutron flux to zero and decreasing the muon flux by a factor of approximately 2000 [9]. The laboratory features a useful surface area of $40\,\mathrm{m}^2$.

4.11 Other submissions – Does not apply.

4.12 Other information – Does not apply.

5 Requested modules/funds

5.1 Basic Module

5.1.1 Funding for Staff

The following staff is requested for the successful completion of this project within DELight:

- **0.5 Postdoctoral Researcher for 4 yrs:** One postdoctoral researcher, ideally with previous experience in low-background methods and rare-event-searches as well as in Monte Carlo methods, will be hired for the full funding period. We plan to hire a full-time (100%) postdoctoral researcher, the other half will be funded by project P3 which will also be conducted mainly at the University of Freiburg. The duties of the postdoctoral researcher will thus be equally shared between projects P3 and P4.
  Within this project P4, the postdoctoral researcher will be responsible for the feasibility study and risk assessment of operating DELight in an underground laboratory with special emphasis on the Vue-des-Alpes laboratory. Further the researcher will develop the mechanical shield in close collaboration with P3 and the UFR engineer and technician. In addition the researcher will assist the doctoral researcher (see below) in the effort of setting up a fully functional slow control system for DELight.
  The DFG Personnel Rates for 2023 foresee annual costs of 40,050 €/year for half of the 100% TV-L E13 position for the postdoctoral researcher, which amounts to **160,200 €** in total.
- **1 Doctoral Researcher for 4 yrs):** One doctoral student, ideally with a background in experimental (astro-)particle or nuclear physics, will be hired for the full funding period. Four years are an adequate duration for a doctoral degree in experimental particle physics which includes setting up a new experiment. The four years duration will enable the doctoral researcher to contribute to DELight from its very beginning up to the delivery of first science results.
  The doctoral researcher will be responsible for customizing Doberman to align with the requirements of DELight. They will also provide support and interface with the other projects (P1 and P2) in the process of selecting sensors for integration into the slow control system. Furthermore, they will establish the slow control computing infrastructure, including the main server, databases, and PLCs, and conduct thorough testing of the system. In close collaboration with the postdoctoral researcher and the other projects, the doctoral student will develop an alarm system that can report significant deviations from normal operation. This system will be designed to avoid overwhelming operators with excessive alarms, which could otherwise reduce their situational awareness. The doctoral researcher will be engaged in the data analysis process, with a specific focus on evaluating the acquired slow control data in order to establish criteria for selecting data.

The DFG Personnel Rates for 2023 foresee annual costs of 55,575 €/year for the 75% TV-L E13 position for the doctoral researcher, which amounts to **222,300 €** in total.

Both researchers will also contribute to the construction and installation as well as operation and commissioning/characterization of DELight. They will contribute to the sensitivity paper, data analysis and the publication of the first results.

5.1.2 Direct Project Costs

5.1.2.1 Equipment up to € 10,000, Software and Consumables

For successful completion of DELight Project 4, resources for equipment up to € 10,000 are required. The total costs are estimated to be **94,000 €**. Table 4.2 summarizes the breakdown of the cost. More detailed information are given below.

Table 4.2: Overview of requested resources for equipment up to € 10,000, software and consumables.

Item	Description	Prize in € incl. VAT
1	Slow control server and disc storage	6,500
2	Slow control I/O modules	7,500
3	Temperature readout	2,500
4	Electrical control cabinet	7,500
5	UPS battery system	5,000
6	Gamma-ray shield	65,000

Item 1. The slow control system necessitates several components, including a primary server responsible for hosting the historical database, a secondary database for storing configuration data, and the primary instance of the slow control software. During the initial phase of DELight, we anticipate accumulating approximately 1 terabyte (TB) of historical data. To efficiently manage and store these data, we plan to use InfluxDB, which recommends a minimal configuration of at least 4 CPU cores, 4 GB of RAM, and 2000 IOPS (input/output operations per second). To ensure data safety, we intend to implement a RAID (redundant array of independent disks) level 5 configuration, which will require a minimum of 4 disks. Based on current pricing information, we estimate the total cost for these components to be approximately 6,500 €.

Item 2. The slow control system further requires both digital and analog input and output (I/O) modules. Drawing from our experience with similar-sized experiments, we anticipate the need to read data from approximately 30 analog sensors and control around 25 digital signals, such as relays to monitor pump status or actuate valves. Following the solution outlined above, which utilizes Revolution Pi modules, these numbers correspond to approximately 15 modules and, at current prices, result in an estimated cost of about 7,500 €.

Item 3. We anticipate installing approximately 20 Pt100-based temperature sensors in the laboratory, positioning them both outside and inside the shielding. Based on our previous experience, we estimate that three readout modules will be necessary. When factoring in the cost of the sensors themselves and the cables required for proper wiring, we expect the total expenses to be around 2,500 €.

Item 4. At least one electrical control cabinet including hardware components and a human-machine interface will be required. The hardware components include items such as relays, 24/48V power supplies, fuses, and all the necessary parts for wiring these components. We anticipate that the cost for these items will be approximately 7,500 €.

Item 5. To assess and control the status of the system, we require a battery-based uninterruptible power supply (UPS) for the main slow control server and the modules responsible for communicating with the sensors and actuators. Based on recent quotations for a similar experiment, we estimate the cost to be approximately 5,000 €.

Item 6. DELight's gamma shield will be constructed using various components, including robust aluminum profiles, a steel base plate, and connecting elements. We'll encase it in either aluminum plates or acrylic glass, with heavy-load wheels for easy access. The shield's design and costs are uncertain due to factors like DELight's cryostat size and background requirements, to be determined during phase-I. Assuming a basic cylindrical shape for a 1 m inner diameter and 2 m height, initial estimates based on the GeMSE shield indicate costs of 210,000 €. However, for phase-I's reduced background requirements, we plan a modular design that can be further optimized if needed for DELight's phase-II. The estimated cost for this design is approximately 65,000 €.

5.1.2.2 Travel Expenses

For DELight Project 4 a total of **32,600 €** travels funds are required to cover the following costs:

- **International conferences.** The attendance of and contribution to relevant international conferences, like IDM (the International Conference on the Identification of Dark Matter), LDW (Meeting of the Light Dark World International Forum), TAUP (the International Conference on Topics in Astroparticle and Underground Physics), LTD (the International Workshop on Low-Temperature Detectors) or LIDINE (LIght Detection In Noble Elements), provides important visibility, networking, and interpersonal communication opportunities strengthening DELight and the careers of its scientists. We estimate the cost for a typical 5 day long international conference or workshop at 1,500 € and foresee travels to 4.5 conferences in the 4 years funding period. (0.5 trips indicate that the other half is funded by DELight Project 3.) The total amount required is thus **6,800 €**.
- **DPG Spring Meetings.** Doctoral and postdoctoral researchers, as well as the DELight project which they represent, strongly benefit from attending the annual Spring Meeting of the DPG (German Physical Society) every year. Especially doctoral researchers use this opportunity for their first presentations to the wider scientific community. We estimate the costs for a 5 day long trip to the DPG Spring Meeting at a Germany city at 1,000 € and plan with six trips during the funding period, which amounts to **6,000 €**.
- **DELight in-person meetings.** This project is tightly connected to several other DELight projects (e.g., P1 – cryogenic setup and ^{4}He cell, P2 – MMC detectors, P3 – Low-background

environment, P6 – Science analysis), which requires close coordination with our colleagues. This requires occasional travel to the other institutions for day-long in-person meetings. Here we can clearly benefit from the close geographical proximity of the three DELight institutions. We estimate the average costs for a short trip at 150 € and anticipate four short trips per year. This amounts to **2,400 €** in total. (The costs for traveling to or hosting the two in-person collaboration meetings per year are covered by the Coordination Project.)

- **Installation shifts.** The installation of the DELight detector is a collaborative effort involving the entire RU. This includes construction and installation of hardware which requires coordinated work over multiple days in the form of installation shifts. While members of the groups at KIT and UHD can commute daily between Heidelberg and Karlsruhe, the same is not true for members of the groups at Freiburg. In this case, funding for extended stays at the partner institutions is required. A typical length of a shift is 7 days with an estimated cost of 1100 €. We anticipate that one shift per person funded via the RU and one externally funded member of the RU is required in year 1 and two shifts in years 2-3. Thus 2.5 people will each take five shifts in total, adding up to **13,800 €**.
- **Trips to the VdA laboratory.** The VdA laboratory is located in the Vue-des-Alpes road tunnel in Switzerland. It can be reached by car in about one hour from Bern (65 km) or in about 2.5 h from Freiburg (200 km). Regular trips to the tunnel are required to assess and prepare the laboratory for an underground science campaign of DELight. For this project we estimate typically six trips/year, taking into account that also in the context of project P3 regular travels to Vue-des-Alpes will happen in order to operate and maintain the HPGe spectrometer GeMSE that is loacted in the VdA laboratory. The cost of a single trip depends on the means of transportation (train, car, train discount card, number of people traveling); based on previous experience it is in average 150 € per person and trip. The total cost foreseen is thus **3,600 €** in total.

5.1.2.3 Visiting Researchers (excluding Mercator Fellows)

Does not apply. In case short term visits of external researchers become necessary, their visits will be supported by the applicant's institutional funds or via long-term fellowships[5] offered by the Freiburg Institute for Advanced Studies (FRIAS) of the University of Freiburg.

5.1.2.4 Other Costs – Does not apply.

5.1.2.5 Project-related Publication Expenses

Does not apply. Project-related publications will be published in journals of the Sponsoring Consortium for Open Access Publishing in Particle Physics (SCOAP^3) where no extra costs occur. In addition, all articles will be posted on the open-access `arXiv` preprint server.

5.1.3 Instrumentation

5.1.3.1 Equipment exceeding € 10,000 – Does not apply.

[5] https://www.frias.uni-freiburg.de/en/funding-programmes/frias-fellowships

5.1.3.2 Major Instrumentation exceeding € 50,000 – Does not apply.

P5 - Data acquisition and computing

Applicant: Belina von Krosigk (Heidelberg)
Co-applicants: Torben Ferber (Karlsruhe), Markus Klute (Karlsruhe)

Project Description

DELight is a new particle physics experiment that can only be realized through the confluence of all six projects. Each project plays a fundamental and unique role, where the project described in the following is responsible for the **data acquisition (DAQ) at hardware and software level and for the computing infrastructure**.

The DAQ system, which includes the trigger system, together with the computing infrastructure are fundamentally required in order to reliably identify energy depositions, to collect and process the data, to write both raw data and processed data to disk, and to manage data storage and access for analysis. The processing and computing infrastructure will analogously manage simulated data sets. In order to maximize the science output of the experiment, two aspects are crucial for DAQ and computing: On the one hand deadtime must be avoided in order to maximize the exposure and thus the sensitivity to the dark matter scattering cross section. On the other hand the trigger threshold must be as low as possible to be sensitive to as low possible dark matter masses without significantly increasing the noise trigger rate.

The trigger system in case of DELight will be a two-staged trigger, where the level-1 (L1) trigger occurs on hardware-level and the subsequent level-2 (L2) trigger occurs on software-level. The L1 trigger evaluates the raw time series output of the MMC-based wafer calorimeters after digitization and decides whether an elevation above the baseline of these traces is expected to be noise or signal. It is thus the baseline resolution together with the ability of the L1 trigger to distinguish between noise and signal down to very low energy depositions, which defines the trigger threshold. In phase-I of DELight, the detector system will consist of about fifty wafer calorimeters, each providing one channel for the DAQ to readout. The design goal for the baseline resolution of each wafer calorimeter is at 5-6 eV, which corresponds to a design goal for the trigger threshold of about 20 eV. In phase-II of DELight, the detector system will be upgraded to ultimately achieve full surface coverage by adding further wafer calorimeters, and thus readout channels. At the same time a higher energy resolution and lower trigger threshold will be aimed for. The goal of this project is thus a scalable, deadtime-free DAQ with a highly efficient, low-energy trigger system followed by powerful event reconstruction on software level, tied into a streamlined, low-maintenance computing infrastructure.

1 Starting Point

State of the art and preliminary work

The field of experimental particle and astroparticle physics is very dynamic, with new technological developments and advancements occurring regularly. Data acquisition (DAQ) and computing requirements in an (astro)particle physics experiment are driven by the science goals and have to address various challenges, some of which are common to many experiments, some of which are unique to a certain detector. The state of the art in DAQ and computing is thus constantly evolving.

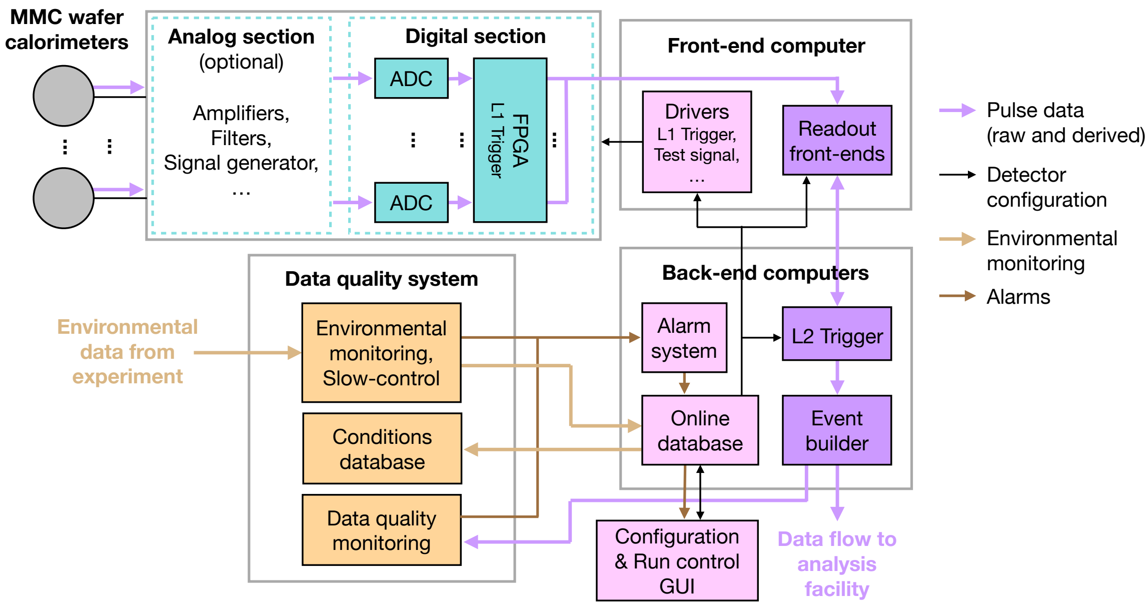


Figure 5.1: Draft architecture of the DELight DAQ system showing the DAQ hardware (light blue) and software (pink and purple), and the data quality system (orange). The environmental monitoring and slow-control are part of P4 and interface with P5 as shown here.

Data rates and volumes. A typical high-energy physics (HEP) experiment like Belle II or CMS has to manage data rates of the order of 20 GB/s and has to take first-level trigger decisions within a few μs. The total raw event rates can be as high as 3 kHz and the data written to disk after trigger decisions were taken amount to PBs of raw data. In contrast to that, the event rates during a science run of rare event search experiments are per definition as low as possible. These include direct dark matter (DM) search experiments and low-background neutrino experiments. At the same time, an individual event in these detectors can result in tens of MB and the data rate can exceed hundreds of MB/s during calibration runs. For instance, a single SuperCDMS event can be as large as about 45 MB and XENONnT has observed 250 MB/s during calibration runs. nEXO even anticipates 400 MB/s during calibration.

Common to all these experiments is that their collaborations work to maximize their sensitivity to signal, which typically means using a particle beam with an as high as possible intensity or building a detector with as much target mass as possible and/or pushing their trigger threshold as low as possible, while the deadtime of the DAQ system has to be kept at a minimum and storage space has to be managed economically. Both HEP and rare-event experiments require DAQ systems capable of handling high data rates and volumes while maintaining precision in event reconstruction and a high signal efficiency. Cutting-edge systems utilize advanced electronics, high-speed data links, and powerful processing units to achieve this. Advanced trigger algorithms are employed to keep the event rates and storage space at a manageable level at all times. This is particularly important for experiments located in laboratories with a limited access to the outside world. For example, the connection of Canada's SNOLAB underground laboratory – home to many DM and neutrino experiments – to the surface can handle at most 10 Gb/s which is furthermore shared by multiple

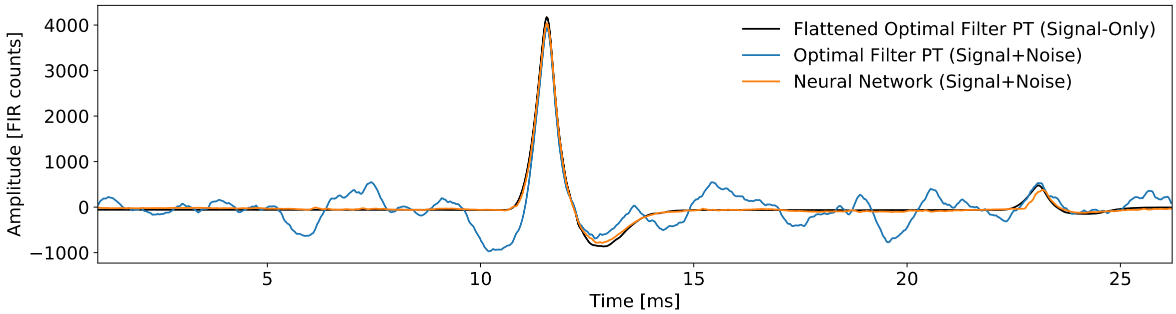
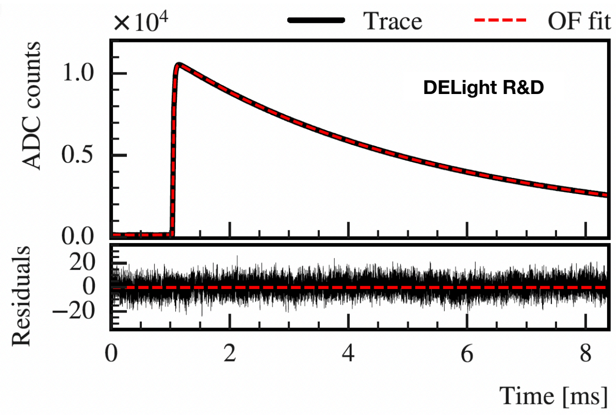


Figure 5.2: Simulated output of the default Finite-Impulse-Response (FIR) filter of the FPGA-based SuperCDMS trigger using an optimal filter (blue) compared to the simulated output of a new neural network module (orange) [1]. The flattened optimal filter output (black) provides a comparison with pure signals in the absence of any noise. Two signals are shown, one with a large energy deposition around 11 ms and one with a small energy deposition around 23 ms. PT stands for "Phonon Total", i.e. the summed trace from all phonon channels.

experiments. The connection to the surface occasionally experiences interruptions, yet the available space underground for storage racks is limited. Thus, trigger decisions have to be taken to maintain a data rate at which experiments can run for at least a day without dumping data.

While DELight will initially be a small-scale experiment, its scalability provides the valuable opportunity for a large-scale experiment in the future and any DAQ system and computing infrastructure built and set-up today should anticipate future upgrades to continuously improve the system and grow expertise with it, and for an economical use of resources.

Advanced triggering and event selection. (Astro)particle physics experiments generate enormous amounts of data, much of which may be background or noise. Both background and noise typically further increase significantly with lowering the trigger threshold and an early event selection will reduce the requirements on the DAQ system and computing further downstream the pipeline. Another challenge, which is of relevance to low-threshold detectors like DELight, is the fact that reading data from the circuit board can possibly add to the baseline noise of the used sensors. This has been observed in the SuperCDMS dark matter experiment, using transition-edge sensors (TESs) to measure phonon signals generated by particle interactions in cryogenic silicon and germanium crystals. The baseline noise, however, determines the level of the trigger threshold and even if the raw data rates are manageable, a reliable trigger decision on hardware level *prior* to readout is crucial in such a scenario to keep the trigger threshold as low as possible. In both cases, high data rates and an increased noise environment, intelligent trigger algorithms provide the means to selectively capture and process only the most interesting events and thus reduce the data load and keep the trigger threshold as low as possible. The current generation of DM experiments is moving in two main directions. "Weak-scale WIMP" experiments, sensitive to GeV- to TeV-scale DM particles, move toward maximizing the target mass, which is coming along with hundreds to thousands of readout channels. Examples are DARWIN [2] and DarkSide-20k [3], with an anticipated fiducial target mass of 40 t of liquid xenon (LXe) and 20 t of liquid argon (LAr), respectively. "LDM" experiments, aiming at exploring the sub-GeV mass scale, move toward an ultra-low trigger threshold and a dark count rate close to the limit set by quantum statistics. Examples are SuperCDMS-HVeV [4] and SENSEI [5], which both achieved sensitivity to single charges. Also DELight will be an LDM detector pushing



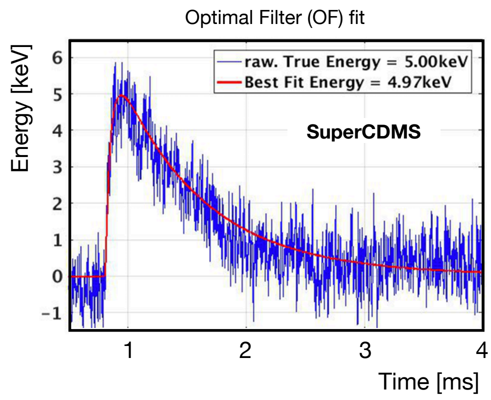


Figure 5.3: (left) Typical raw trace (black solid) from an MMC as is currently used as part of DELight R&D. Also shown is a template scaled with an optimum filter amplitude (red dashed) and the difference between raw trace and scaled template (plot below). (right) Typical raw trace (blue solid) from a SuperCDMS crystal sensed with TES-based detectors together with a template scaled with an optimum filter amplitude (red solid). Note that the y-axis of the SuperCDMS trace is calibrated, while the MMC trace's is not.

toward a world-leading low threshold [6]. LDM experiments are typically smaller than weak-scale WIMP experiments, initially. But also in their case future generations will increase the target mass and with it the number of readout channels. Either direction presents both technological challenges and opportunities that are new to the (astro)particle physics community and the following trends are being observed: experiments are either designing custom electronics using Field-Programmable Gate Arrays (FPGAs) to perform initial data processing at the front end (e.g. SuperCDMS [7], DarkSide [8]) or are moving to pure software triggers (e.g. XENON [9, 10]). FPGAs can be programmed to perform real-time data compression, trigger decision making, and event filtering before data is sent to subsequent stages of the DAQ system. Also Graphics Processing Units (GPUs) and other parallel processing architectures are being integrated into DAQ systems to handle the increasing data processing demands. These technologies accelerate pattern recognition, contributing to quicker data interpretation and enabling a reduction of the data throughput at the first stages of the DAQ system. Many experiments further explore machine learning techniques, including neural networks, and their incorporation into the trigger system to aid in the real-time data analysis and event classification (e.g. [1, 11]). These methods can enhance the accuracy of event identification at trigger level and can additionally reduce the need for post-processing. Independent of the detailed design of the trigger system, the goal is an increased scientific flexibility and sensitivity with easily manageable systems. And in all cases, software triggers are integral parts of the DAQ system. Most experiments are developing event builder software, some by leveraging existing DAQ frameworks, such as MIDAS [12] (e.g., DEAP, SuperCDMS, and DarkSide), while others develop their own open-source DAQ codes (e.g., XENON [13, 14]). As DAQ becomes a part of analysis through trigger decisions, DM experiments increasingly need to address system design questions that encompass both DAQ and analysis, which forms a strong link in this particular proposal between this project and Project 6.

Advanced computing and network infrastructure. Advanced computing played a crucial role in the analysis of the vast amounts of data that lead to the discovery of the Higgs boson by the ATLAS and CMS experiments at CERN's LHC. Not only HEP experiments, though, but also numerous ongoing and upcoming direct DM experiments, such as XENONnT and SuperCDMS, are relying on advanced computing for storing, managing, processing, and analyzing their data and to allow for increasingly sophisticated Monte Carlo simulations to model particle interactions and detector responses accurately, aiding in experimental design and data analysis. Advanced computing typically involves parallel processing, where multiple processors or computing nodes work together to solve a problem concurrently, a concept that is often further extended using multiple interconnected computers or clusters. It frequently incorporates machine learning techniques to automate tasks, make predictions, classify data, and discover patterns. In all these efforts, efficient data compression techniques are essential to reduce storage and transmission demands and researchers world-wide work on developing lossless and lossy compression methods that preserve the critical information while minimizing data volume. Furthermore, computing grids and reliable high-speed data transfer are essential, especially for experiments that are spread across multiple geographic locations. These experiments rely on dedicated high-bandwidth networks and protocols optimized for transferring data in real-time and to process and analyze this data efficiently.

While DELight will start with comparatively small computing demands, the goal must be to minimize parameters like the total data size that is written to disk while maximizing the science output, and to set up a computing and network infrastructure that can be easily scaled up as both the experiment and the collaboration is planned to grow in the future. A smart, forward looking computing solution will help reduce the experiment's ecological footprint, while maintaining its science goals. Another point crucial for DELight's competitiveness in a fast moving science environment is the fast access to processed data. Advances made in computing and network infrastructure are thus an important aspect in the design of DELight.

Preliminary work. B. v. Krosigk was the project manager and one of the core-developers of the custom SuperCDMS DAQ software using the MIDAS system, which is by now successfully commissioned and running at all active SuperCDMS laboratories including SNOLAB. The core components of this **DAQ software** package are

- drivers for the detector control and readout electronics and the high voltage power supply,
- readout front-ends,
- a staged trigger system with one FPGA-based and two software triggers,
- an event builder,
- an online database,
- a history database,
- and a web-interface.

Design goals of the SuperCDMS DAQ software included deadtime-free triggering with low energy thresholds, the capacity to handle high rates during calibration data-taking in order to minimize the DM search livetime lost to calibration running, data throughput rates within the capacity of the laboratory's network bandwidth, simple and intuitive detector and trigger configuration tools and databases that minimize the chances of operator error and provide easy remote and online use, a straightforward interface to data quality and environmental monitoring, and the ability to easily incorporate a mix of different detector designs. The goals of the DELight DAQ are almost identical and the design of the DELight DAQ architecture can easily follow that of the SuperCDMS DAQ system resulting in the draft architecture shown in Fig. 5.1.

To date, B. v. Krosigk is the operations coordinator of the SuperCDMS DAQ and trigger system [7] and explores the use of neural networks within the **FPGA-based first-level trigger** [1]. An example output of the recently designed neural network module is compared to the output of the Finite-Impulse-Response (FIR) filter in its default design in Fig. 5.2. In either case, the output is subsequently fed into the threshold, peak search, and trigger logic within the FPGA firmware and the improved signal-to-noise ratio of the neural network module, that is demonstrated in Fig. 5.2, resulted in a reduction of the trigger threshold of about 22% in an initial proof-of-concept study using trigger simulation [1]. Great similarities between SuperCDMS raw traces and the type of raw traces as expected for DELight (see Fig. 5.3) will allow to adopt ideas and conclusions from this line of FPGA-based trigger work for DELight.

T. Ferber is the project coordinator of the Belle II Neurotrigger project which provides real-time track-reconstruction for the Belle II experiment. He explores **Graph Neural Network (GNN) based algorithms for calorimeter triggers** and for tracking [15]. A critical bottleneck for these applications in real-time was the building of large graphs on FPGAs that has recently been established [11] and that is directly transferable to the non-uniform sensor layout of DELight. B. v. Krosigk and T. Ferber have already collaborated in the past on algorithms optimized for highly efficient event selection and in particle identification techniques [16].

M. Klute designed the storage manager system within the CMS experiment, tailored for managing and retrieving massive experimental data sets. In addition, he lead the software and computing coordination area for the CMS collaboration. This project encompasses the largest scientific software stack as well as processing and analyzing petabytes of data annually, disseminated across a global network of more than 100 computing centers, representing one of the largest computing grids worldwide. Building on this extensive experience, M.Klute is currently deploying **computing infrastructure at KIT**, building an **analysis facility** for the DARWIN DM experiment. A token-based authentication system will provide access to all collaboration members, even if they are not affiliated with KIT. This analysis facility will serve as a starting point and template for DELight.

The groups of B. v. Krosigk, T. Ferber, and M. Klute developed and set up a first version of a **raw data processing and event reconstruction pipeline** that allowed the analysis of MMC data [17, 18]. This data was provided by S. Kempf, the leader of project P2. The raw data processing within this software package includes the energy estimation of the signal pulses in units of Analog-to-Digital Converter (ADC) counts, using an optimal filter based fitting algorithm as demonstrated in Fig. 5.3. Using this software for the MMC data analysis, an unprecedented FWHM resolution was achieved [18]. Although at the time of code development only one readout channel was used for the analysis, the pipeline was already set up to allow for multiple channels as will be the case in DELight. The first-level processing of raw data is at the interface with project P6.

2 Objectives and work programme

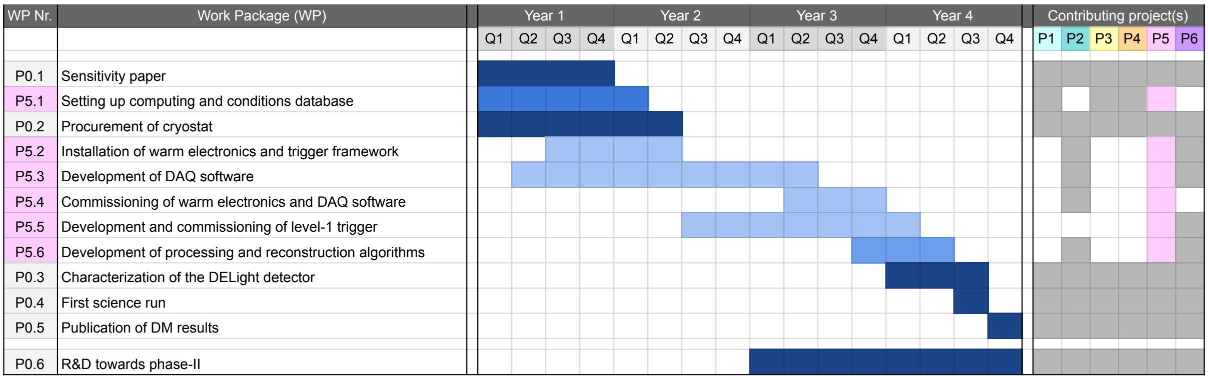


Figure 5.4: Summary of the P5 work programme. The work package (WP) numbers indicate the respective lead project (here P5) and the count within that project's list of WPs. The P0 identifier is used for WPs that are equitably performed by all participants of the RU. The shades of blue within the timeline indicate the amount of contributing projects. The lightest blue is used for WPs only conducted within P5 and one second project. The darkest blue is used for WPs to which all projects P1 - P6 contribute. The rightmost block of the program signals the lead project (color) and the further contributing projects (gray).

2.1 Anticipated total duration of the project

The total duration of this project is fully aligned with the timeline of DELight phase-I as described in Sec. 2.2 of the "Overall Description of the Research Unit and the Coordination Proposal". The anticipated total duration of the project is four years.

2.2 Objectives

The primary science goal of DELight is to search for DM particles with the lowest possible masses. The lighter the mass of the particle, the smaller the energy depositions. The DAQ and trigger system will thus be designed to identify very small energy depositions at a threshold as low as at most three standard deviations above the noise level (see P2). Three standard deviations is the default trigger target goal because accidental noise triggers are by definition comparatively rare even with a simple amplitude-over-threshold trigger algorithm. More sophisticated trigger algorithms and event classification on L1 trigger level provide the opportunity to further lower the trigger threshold without increasing the noise trigger rate. An example demonstrating this aspect is given in Fig. 5.2, where a very small energy deposition (at around 23 ms in the shown time series) can be safely identified in a neural network based trigger algorithm whereas a simpler algorithm cannot distinguish the energy deposition from noise. Respective advanced trigger algorithms will be explored and developed within P5 with the objective to surpass the default threshold goal. The planned science-grade data exposure in the first science run is 1 kg·d corresponding to less than a day of data taking with a 10 ℓ He cell (see P1) and under the idealized assumptions of a duty cycle of 100%, and no exposure reduction on analysis-level. The work program summarized in Fig. 5.4 schedules 3 months for science data taking, ample time to achieve the requirement of 1 kg·d exposure with the goal to maximize the exposure beyond this requirement.

The wafer calorimeters described in P2 will be read out in about 50 channels and are expected to achieve $\mathcal{O}(10\,\mu\text{s})$ signal rise-times. To resolve these rise-times, relevant for event reconstruction, a sampling rate of 1 MS/s is adequate. Using 16 bit digitizers will result in 2 MB/s per channel, totaling up to about 7.6 TB/d (100 MB/s), when the data is read out continuously. A bandwidth of at least 100 MB/s is thus required for a continuous raw data acquisition. A system capable of acquiring raw data continuously is highly beneficial for diagnostics and crucial for noise characterizations to also capture potential low frequency noise. At the same time, continuous readout becomes untenable for long measurement campaigns. Running for one year with an 80% duty cycle would generate a disproportional raw data size of about 3 PB/yr. Thus, in addition to a continuous mode, a triggered mode will be developed and implemented in which only regions in the raw data stream are acquired that contain a potential energy deposition in the helium volume. The respective L1 trigger will run on a field programmable gate array (FPGA), designed to identify signal-like events down to very small energy depositions while efficiently dismissing noise fluctuations. To capture an event together with important noise information right before and after the resulting pulse, 50 ms long traces will be readout per triggered event. Reference [19] predicts a background rate of notably less than 1 Bq for the HeRALD design, which is well within the goal for DELight (see P3). Assuming a trigger rate of 1 Bq will reduce the raw data size to about 150 TB/yr for science runs. The event rate is typically higher during calibration runs. Calibration data, however, only need to be acquired over significantly shorter periods of time to collect about the same statistics as during science runs. The decay rate itself can be controlled to match the system capacities. A further reduction of the raw data size will be possible by optimizing the event selection with a software based L2 trigger working in concert with the L1 trigger.

The data that are read out are streamed to the analysis and storage facility at KIT. Data streams will be kept on a fast storage system for analysis tasks and long term storage will be provided by a tape system. A data bookkeeping system will track data streams from calibration and science runs. DELight members gain access to the infrastructure via a token-based authentication system.

An additional data quality system will be set-up in co-work with project P4, which is designing and implementing the environmental monitoring system and slow control. A draft of the DAQ architecture, including the data quality system, is shown in Fig. 5.1. The DAQ system will use two core databases: a conditions database and an online database. The online database is in charge of real-time communication between the data quality system, the DAQ software, and the DAQ hardware and the conditions database will contain run information such as run type, wafer calorimeter configurations, channel states, and trigger rates. The conditions database will additionally tap slow control (SC) data from the InfluxDB database (developed in project P4) as necessary e.g. for run control decisions or to tie the information to the science data by including them in the raw data stream. The details of this hand-shake between the SC system and the DAQ system will be developed in collaboration with project P4.

In conclusion, the overall objective of P5 is a deadtime-free DAQ with a highly efficient, low-energy trigger system followed by fast data processing and powerful event reconstruction on software level. The DAQ, trigger, and computing system will be designed to maximize the science output of DELight while being resource-conserving and scalable. The milestones towards this goal are the set-up of the computing infrastructure, the conditions database, and the data management system, the development of the DAQ software, L1 trigger, and the signal processing and event reconstruction algorithms, the installation of the electronics and the trigger system and eventually their commissioning. These milestones are summarized in Fig. 5.4 and are integrated in the overall work programme of DELight as shown in Fig. 5 of the overall RU description. They interface with all other projects of the RU and either benefit from information from other projects or will provide them important information. The steps towards achieving the objective of this project will be described in the following work programme.

2.3 Work programme including proposed research methods

The work programme of P5 is guided by the work packages listed in Fig. 5.4. These work packages can be divided into two categories, one where P5 leads the respective efforts (P5.1-6) and one where the work packages are equitably performed by all participants of the RU (P0.1-6).

P5.1: Setting up the computing and conditions database

Computing. Our objective is to establish a dedicated computing infrastructure at KIT tailored to support the unique needs of the DELight experiment. The system will provide both secure access for our research team and optimal data handling capabilities. Central to the infrastructure will be a dedicated server, acting as the main gateway for all users and computational tasks. To ensure a secure and restricted environment, this server will use a token authentication mechanism. The required compute resources will be scalable to match increasing demands. In tandem with the server setup, we will curate a specialized software stack. This stack will include applications and utilities chosen based on the experimental requirements. It will encompass tools vital for data processing, visualization, and analysis. Our aim is to have these tools work in harmony with the DAQ system, presenting an integrated and user-friendly environment. One of the cornerstones of this project will be our storage infrastructure. Directly interfaced with our primary server, this system will be designed to host both experimental data and the accompanying simulations. For archival a tape-system backend hosted by GridKa will be used.

Conditions database. We propose the incorporation of a conditions database, seamlessly linked with our detector control and safety system. This database is primarily envisioned to collect experimental conditions data, such as detector configurations, run types, temperature readings, and other pivotal parameters. It either obtains these data directly from the DAQ system or draws relevant Slow Control data from the InfluxDB database, which will be developed in project P4. The role of the conditions database within P5 is to include the collected information into the raw data stream, enabling the systematic analysis of features observed in the raw data and to identify potential correlations with any of the stored conditions. By systematically storing metadata, we lay the foundation for a deeper, retrospective analysis, facilitating an enriched understanding of the experimental data. Recognizing patterns, deviations, or correlations in metadata, such as temperature variations or configuration changes in the DAQ, will empower us to interpret experimental outcomes more accurately and holistically. The development of the conditions database within the DAQ system and the InfluxDB database within the SC system will be a coordinated effort between projects P4 and P5.

P5.2: Installation of warm electronics and trigger framework

Front-End Electronics. The digital section shown in Fig. 5.1 is what is referred to as "warm electronics" and consists of 16 bit ADCs, with enough channels to support about 50 readout channels, and of an FPGA running the L1 trigger. The warm electronics interface with the cold (SQUID[6]) electronics that are developed and installed within P2. Within this work package, all warm electronics will be installed and prepared for commissioning within package P5.4.

Trigger Framework. The trigger system plays a crucial role in data reduction and consist of the two aforementioned stages within DELight, L1 and L2. During phase-I of DELight, one FPGA will receive raw data information from all MMC-based wafer calorimeters and thus receives in principle all the information needed to take a global decision without an additional software-based L2 trigger. Anticipating a future upgrade of DELight, however, more FPGAs will be employed as the number of calorimeters grows. The L1 trigger will thus loose the ability to combine the information from all calorimeters and to identify global patterns. The trigger system will consequently outsource top-level decisions based on primitive information to the software level (see P5.3) from the very beginning. The L1 trigger will generate these primitive information based on the raw waveforms it receives from the MMC-based wafer calorimeters. The trigger FPGA will be implemented as part of the front-end electronics and a simple amplitude over threshold algorithm will be employed initially, and as part of this work package, to develop the hand-shake with the L2 trigger. A more sophisticated and more powerful trigger logic will be developed as part of work package P5.5.

P5.3: Development of the DAQ software

The DAQ, together with the data management set up within P5.1, is a critical component of a particle physics experiment which ensures the efficient acquisition, handling, storage, and analysis of the data generated by that experiment and generated in simulations. Such a system comprises various elements and strategies to manage the complete data lifecycle from acquisition to analysis. Key components of the DELight DAQ software will be developed in this work package and follow the logic depicted in Fig. 5.1.

DAQ software. The DAQ software will be responsible for controlling both the MMC detector system and the L1 hardware trigger, for deciding which of the L1 triggered waveforms to read out based on L2 trigger decisions, for reading out the respective raw data, for event building, for data quality (DQ) monitoring with a respective alarm system, and for the run control. These individual components allow for a modular design of the DAQ software and the software can be taken online the moment the initial framework is set up and the detector control and data readout clients have been developed. An integrated "dummy readout" mode, using a software-generated dummy data stream, will enable first tests already prior to the availability of MMC-based wafer calorimeters, electronics, and the L1 trigger FPGA. While all components are required for the acquisition of high

[6] SQUID: superconducting quantum interference device.

quality data at a reasonable data rate, this scheme will allow to develop and test the software at each step in the development under this work package.

The MMC-based wafer calorimeters as well as the expert-level control of the wafer calorimeters and SQUIDs will be developed in project P2 and close collaboration between P2 and P5 will allow for developing and optimizing the top-level detector control and readout software, embedding the software modules developed within work package P2.2 of Project 2. The data quality monitoring relies on information from the environmental monitoring and they together form, in combination with the slow control and conditions database, the DQ system (see Fig. 5.1). Environmental monitoring and slow control are under the purview of P4 and the DQ system is the interface between P4 and P5. The two teams will therefore work closely together on this aspect.

Level-2 trigger. The L2 trigger is part of the DAQ software. It is described separately, though, to provide a better picture of the whole trigger system which includes the L1 hardware trigger. The L2 trigger will receive only primitive information from the L1 trigger such as which of the calorimeters triggered at level-1, and the amplitude and timestamp of the corresponding signal pulse per calorimeter. It will be developed to identify particle-event-like timing patterns between the signaling calorimeters and to identify pile-up, i.e. two or more overlapping signals that are too close in time to be sufficiently resolved individually. The latter will be important during calibration data taking, when the data rate may be high enough to cause frequent pile-up events. The timing difference that defines a pile-up event, and whether or not these events will be vetoed, are free parameters that can be controlled by the user. Once the L2 trigger identifies a potential particle interaction that is not vetoed, either by the L2 trigger itself or by other parts of the system that take monitoring information into account, it will instruct the readout software to acquire the respective waveform data for storage and further processing.

P5.4: Commissioning of warm electronics and DAQ software

In this work package all hardware components of P5 and the DAQ software will be commissioned in collaboration with the group members of P1 (helium cell) and P2 (MMC-based wafer calorimeters). Commissioning is completed once the whole data path starting with a signal generated in the MMC-based wafer calorimeters ending with the data stored at the analysis facility, as depicted in Fig. 5.1, is functional. This milestone is an important predecessor for the characterization campaign of the helium cell and detection system (work package P0.3). Also the L1 trigger is included in this path and is required to function. However, the firmware does not need to be finalized at this point and upgrades of individual modules within the trigger logic are still anticipated as part of the characterization campaign. The final commissioning of the L1 trigger, as it will be used for the first science run (work package P0.4), is thus part of package P5.5.

P5.5: Development and commissioning of level-1 trigger

The L1 trigger searches the waveforms in real-time, using algorithms running in an FPGA, for evidence of an energy deposition. Within this work package, the L1 trigger logic will be designed, developed, and commissioned. In order to achieve an efficient trigger threshold close to the baseline noise, and thus at very low energies, without an unnecessarily high trigger rate caused by noise fluctuations a design goal will be to increase the signal-to-noise ratio of the waveforms. This will be obtained by applying an optimal filter to the raw waveforms as part of the L1 trigger logic, following the example of the SuperCDMS L1 trigger [7]. Another core component of the trigger logic is the algorithm that identifies an energy deposition. In a simple amplitude-over-threshold routine the amplitude of noise fluctuations will ultimately limit the trigger threshold to a level at which these fluctuations do not yet dominate the trigger rate. We demonstrated in Ref. [1] that a pulse-shape analysis as part of the trigger can help to further reduce the trigger threshold without increasing the noise trigger rate. Within this work package various pulse-shape discriminating algorithms will be developed and compared before the final design will be chosen and implemented. Design options include both multi-dimensional optimal filters and neural network architectures. The resulting L1 trigger firmware will be initially validated using trigger simulation before it will be loaded onto the hardware for further testing and commissioning.

P5.6: Development of processing and reconstruction algorithms

Processing refers to a series of actions and transformations applied to raw data to convert it into a more usable and/or informative form in preparation for science analysis. It can be split into two categories, online processing for a fast assessment of the data quality that is being acquired, and offline processing for the extraction of relevant event information with a high accuracy. All steps of online processing, starting with the collection of raw data as acquired by the DAQ system and ending with the hand-off of first-level reconstructed data to the analysis platform, will be developed in this work package while offline processing is part of project P6 (science analysis). A core part of processing in general is the application of reconstruction algorithms, providing details on an event like energy, position and timing information. Within the online processing stage the reconstruction must occur almost in real-time but a reduced accuracy is acceptable compared to the offline reconstruction that is part of analysis. If the data quality, as determined by the online reconstruction stage, is outside a predefined range, an alert will be issued. The deliverable of the processing pipeline are two sets of data files, one with the raw data and one with the preliminary event information extracted during online reconstruction. This work package is completed, once the generation of these files has been confirmed and validated.

Online reconstruction and offline reconstruction share various steps, such as the calculation of power spectral densities (PSDs) and the calculation of energy estimators using an optimal filter based template fit. Also the required level of accuracy achieved during online reconstruction will be informed by the requirements for a high quality science data analysis. For both of these reasons, project P5 and P6 will collaborate on the development of the reconstruction pipelines. These efforts will directly build on the preliminary processing pipeline that was developed by the DELight authors of Ref. [18], used for the analysis described in that reference.

P0.1-6: Procurement of cryostat, detector characterization, first science data, DELight publications, R&D towards phase-II

The work packages P0.1-6 have no leading project but are equitably performed by all participants of the RU. They are an expression of collaboration within the entire RU and thrive on the strong synergies between the projects. The activities of the RU during phase-I of DELight are framed by two main publications, a sensitivity paper (P0.1) at the beginning of the funding period and the publication of the first science results (P0.5) at the end of the funding period. These publications require input from all projects and expertise from all members of the RU and will help shape the science output of DELight. Several additional publications are planned to be published within the funding period. The cryostat is part of the coordination project and its procurement (P0.2) will be carried out by the RU together, just like the characterization of the whole DELight detector (P0.3) and the DELight operations and monitoring of the data taking during the first science run (P0.4). In parallel to phase-I, the RU will jointly start R&D towards phase-II (P0.6). A few key contributions of P5 will be highlighted in the following.

Characterization of cell and detection system. This task aims for a comprehensive characterization of the entire system that together forms the DELight detector. Project P5 will particularly study the detector response close to the trigger threshold and the performance of the trigger system. It is crucial to understand and model the resolution, and potential non-Gaussianity, of the energy estimation performed by the L1 trigger in order to model the migration of potential DM interactions into or out of the observable energy region above threshold. Any search for the lightest DM masses accessible with DELight must take this effect into account. In parallel to the characterization of the trigger system P5 will work on determining the accuracy of the online reconstruction algorithms. The acquired data will be required to get a full understanding of the DELight detector as well as to prepare the analysis pipeline.

First science run and data analysis. During the first science run(s) of DELight, project P5 will particularly take care of monitoring both the performance of the warm electronics and the data stream from the warm electronics until the raw data and online reconstructed data are written to disk. This includes in particular monitoring the data quality. The acquired data will be the basis of the work of project 6.

R&D towards phase-II. With respect to R&D towards phase-II, the goals of P5 are closely tied to the goals of P2. Project P2 aims, among others, for (i) improving the energy threshold by enhancing the energy resolution of the MMC-based wafer calorimeters, and (ii) full detector coverage of the entire inner surface of He cell. Goal (i) will directly tie into trigger R&D to allow for an as low as possible trigger threshold while still keeping the data output at a reasonable size. Goal (ii) will notably increase the number of channels the DAQ and trigger system will have to cope with, e.g. by implementing an additional trigger FPGA. More channels will naturally increase the data size, but at the same time more information is available to the trigger system. It will be a goal of P5 to exploit these information for a stringent data selection at trigger level while keeping the signal efficiency to a maximum.

2.4 Handling of research data

The same text applies as in Sec. 2.3 of the "Overall Description of the Research Unit and the Coordination Proposal".

2.5 Relevance of sex, gender and/or diversity

Sex and/or gender is not relevant to the research project. Though we strive for a diverse group of researchers, the level of diversity is also not relevant to the research project.

3 Project- and subject-related list of publications

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[2] J. Aalbers, *et al.*, "DARWIN: towards the ultimate dark matter detector," *J. Cosmol. Astropart. Phys.*, vol. 11, p. 017, 2016. doi: 10.1088/1475-7516/2016/11/017

[3] C. E. Aalseth *et al.*, "DarkSide-20k: A 20 tonne two-phase LAr TPC for direct dark matter detection at LNGS," *Eur. Phys. J. Plus*, vol. 133, p. 131, 2018. doi: 10.1140/epjp/i2018-11973-4

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4 Supplementary information on the research context

4.1 Ethical and/or legal aspects of the project

4.1.1 General ethical aspects

We do not anticipate any risks and/or harm to individuals or groups or the environment and/or the potential for other negative effects that might be posed by our research.

4.2 Employment status information

Last name: von Krosigk
First name: Belina
Employment status: W3 professorship at Heidelberg University

4.3 First-time proposal data – Does not apply.

4.4 Composition of the project group

Table 5.1: Individuals who will work on the project but will not be paid out of the project funds.

Name and academic title	Employment status	Institution	Type of funding
Paid by institution			
Prof. Dr. Torben Ferber	Full professor (W3)	KIT	institutional
Prof. Dr. Markus Klute	Full professor (W3)	KIT	institutional
Prof. Dr. Belina von Krosigk	Full professor (W3)	UHD	institutional
Paid by third-party			
Dr. Benedikt Maier	Post-doctoral researcher	KIT	Alexander von Humboldt Foundation

The composition of the group working on project P5 is summarized in Tab. 5.1. The participants bring the following expertise to the project. B. v. Krosigk is an expert in DAQ and trigger systems, specifically for low-threshold calorimeters, and is very experienced in developing, commissioning, and operating such a system [1, 7]. Additionally, vivid knowledge exchange exists with M. Schumann, who is an expert on the XENON DAQ system [9, 10]. The DARWIN members of B. v. Krosigk's group work on a DAQ software system for DARWIN, building on the knowledge and experience from XENON. B. v. Krosigk and T. Ferber have important expertise in CPU- and FPGA-based trigger algorithms optimized for highly efficient event selection [1, 11]. T. Ferber has a track record in real-time event classification techniques and is the lead-author of the Belle II calorimeter reconstruction software, including waveform analysis of the calorimeter raw data [15, 20]. He has many years of experience in detector operation [20], automated data validation, and the development of machine-learning based reconstruction algorithms. M. Klute and B. Maier have longstanding experience in advanced computing [21]. They are leading the CMS Data Management Group and maintain a large CMS computing and storage facility hosted by KIT. M. Klute has a proven track record in the design and implementation of advanced DAQ and computing systems. At the CDF-II experiment, he was responsible for the technical design and deployment of the Event Builder system, an essential component for efficient data collection and processing. Further, he oversaw and executed the comprehensive upgrade of the CDF-II Level 3 trigger system. M. Klute also led the Physics Performance and Dataset (PPD) coordination area of the CMS collaboration. This vital sector ensures the data collected by the CMS detector is of prime quality, suitable for precise physics results. The PPD oversees the creation and management of comprehensive datasets, gauges detector performance in varied conditions, and fosters collaboration with other CMS working groups. By bridging technical aspects with the experiment's physics objectives, the PPD plays an instrumental role in extracting meaningful insights from the data acquired.

The combined expertise will be used to provide a state-of-the-art DAQ, trigger, and computing system using established astroparticle and HEP standards.

4.5 Researchers in Germany with whom you have agreed to cooperate on this project – Does not apply.

4.6 Researchers abroad with whom you have agreed to cooperate on this project – Does not apply.

4.7 Researchers with whom you have collaborated scientifically within the past three years

All respective researchers are included in Sec. 5.7 of the overall description.

4.8 Project-relevant cooperation with commercial enterprises – Does not apply.

4.9 Project-relevant participation in commercial enterprises – Does not apply.

4.10 Scientific equipment

Grid Computing Centre Karlsruhe (GridKa) and Steinbuch Centre for Computing (SCC). The Steinbuch Centre for Computing (SCC) provides a wide range of computing and basic IT services for all KIT members for work in research and teaching, studies, and administration as well as federal services for universities in the state of Baden-Württemberg, such as UFR and UHD, and for national and international projects, such as DELight. These services include the development platform `GitLab` which allows for collaborative and central version controlled software development. DELight already uses, and will continue to use, `GitLab` at KIT to develop, secure, and operate its software, which will also include all DAQ, trigger, and processing software developed within P5. It operates the central-European Tier-1 center GridKa, which is responsible for processing, preparing and archiving the raw data from LHC experiments. GridKa also serves other (astro)particle physics experiments with German participation, like the Pierre Auger Observatory in Argentina and IceCube at the South Pole, and it will be available for DELight computing.

Institute of Experimental Particle Physics (ETP) The ETP at KIT provides analysis infrastructure in form of access to home directories and GridKa (distributed) computing resources. It further operates multiple development machines that each provide access to a `Xilinx` FPGA (currently UltraScale+ VCU118). This includes access to a license server for full Vivado licences. `Xilinx` is a leading FPGA manufacturer and Vivado is the respective software tool suite for which a license is required. The Vivado software is used e.g. for the design, synthesis, and implementation of digital circuits on `Xilinx` FPGAs.

Electronic and mechanical workshops, Kirchhoff-Institute for Physics (KIP) KIP at UHD runs high-quality electronic and mechanical workshops, which together allow for the development and realization of innovative custom products. Project P5, which entails the warm electronics system of DELight, will benefit from the equipment and infrastructure available at these workshops, together with the local workshop expertise, to set-up and test the warm electronics.

High Performance Computing (HPC) at UHD While computing for this RU will be hosted by KIT and managed by the KIT members of this project, UHD provides additional computing services that can be taken advantage of as required. High performance computing is available for researchers of UHD through access to various computing clusters in Heidelberg or by other competence centers for HPC.

4.11 Other submissions – Does not apply.

4.12 Other information – Does not apply.

5 Requested modules/funds

5.1 Basic Module

5.1.1 Funding for Staff

The following staff is requested for the successful completion of this project within DELight:

- **0.5 Postdoctoral Researcher for 4 yrs:** One full-time (100%) postdoctoral researcher with a graduation in experimental (astro)particle physics, ideally with previous experience in DAQ and trigger systems as well as computing, will be hired at KIT or UHD for the full funding period and will be equally shared between projects P5 and P6. A deep understanding of the

analysis demands to achieve a high DM sensitivity is key for the design of the trigger system and first-level reconstruction. And vice versa, a deep understanding of the trigger and first-level reconstruction is extremely valuable for all subsequent stages of data analysis.
Within this project P5, the postdoctoral researcher will be responsible for the development of the DAQ software and data management system and for the installation and commissioning of the warm electronics of DELight (with local support e.g. by the electronics workshop at the Kirchhoff-Institute for Physics, UHD). Another task will be to develop reconstruction algorithms, which directly ties into the researcher's work within P6, and to help supervise and support the P5 doctoral researcher, who will be charged with the trigger system (see below). The postdoctoral researcher will also help with setting up the computing and, in coordination with P4, the conditions database.
The DFG Personnel Rates for 2023 foresee annual costs of 40,050 €/year for half of the 100% TV-L E13 position for the postdoctoral researcher, which amounts to **160,200 €** in total.

- **1 Doctoral Researcher for 4 yrs:** One doctoral student, ideally with a background in experimental (astro-)particle physics or computer engineering, will be hired for the full funding period. Four years are an adequate duration for a doctoral degree in experimental particle physics which includes setting up a new experiment. The four years duration will enable the doctoral researcher to contribute to DELight from its very beginning up to the delivery of first science results.
  The doctoral researcher will develop the trigger framework as well as trigger and processing algorithms, a task that will include software and FPGA-firmware development. An associated task will be to validate and commission the respective algorithms, using both simulations and real data, acquired with R&D MMCs that are part of project P2, and with DELight itself. These algorithms will be a corner stone of any DELight science analysis. The doctoral researcher will also help with the installation and commissioning of the warm electronics.
  The DFG Personnel Rates for 2023 foresee annual costs of 55,575 €/year for the 75% TV-L E13 position for the doctoral researcher, which amounts to **222,300 €** in total.

Both researchers will also contribute to the construction and installation as well as operation and commissioning/characterization of DELight. They will contribute to the sensitivity paper, data analysis and the publication of the first results.

5.1.2 Direct Project Costs

5.1.2.1 Equipment up to € 10,000, Software and Consumables

The DAQ system requires at least three computers with in total 64 logical hyper-threaded cores for the front-end and data quality (DQ) processes (one core per channel for wafer calorimeter readout and control; the remaining cores for DQ) and 32 logical cores for the back-end processes, and one desktop workstation. The estimate for the total cost is **8,000 €**.

5.1.2.2 Travel Expenses

For DELight Project 5 a total of **15,200 €** travels funds are required to cover the following costs:

- **International conferences.** The attendance of and contribution to relevant international conferences, like IDM (the International Conference on the Identification of Dark Matter), LDW (Meeting of the Light Dark World International Forum), TAUP (the International Conference on Topics in Astroparticle and Underground Physics), LTD (the International Workshop on Low-Temperature Detectors) or LIDINE (LIght Detection In Noble Elements), provides important visibility, networking, and interpersonal communication opportunities strengthening DELight and the careers of its scientists. We estimate the cost for a typical 5 day long international conference or workshop at 1500 € and foresee travels to 4.5 conferences in the 4 years funding period (0.5 trips indicate that the other half is funded by DELight Project 6). The total amount required is thus **6800 €**.
- **DPG Spring Meetings.** Doctoral and postdoctoral researchers, as well as the DELight project which they represent, strongly benefit from attending the annual Spring Meeting of the DPG (German Physical Society) every year. Especially doctoral researchers use this opportunity for their first presentations to the wider scientific community. We estimate the costs for a 5 day long trip to the DPG Spring Meeting at a Germany city at 1000 € and plan with six trips during the funding period, which amounts to **6000 €**.
- **DELight in-person meetings.** This project is tightly connected to all other DELight projects, which requires close coordination with our colleagues. This requires occasional travel to the other institutions for day-long in-person meetings. Here we can clearly benefit from the close geographical proximity of the three DELight institutions. We estimate the average costs for a short trip at 150 € and anticipate four short trips per year. This amounts to **2400 €** in total. (The costs for traveling to or hosting the two in-person collaboration meetings per year are covered by the Coordination Project.)

5.1.2.3 Visiting Researchers (excluding Mercator Fellows) – Does not apply.

5.1.2.4 Other Costs – Does not apply.

5.1.2.5 Project-related Publication Expenses

Does not apply. Project-related publications will be published in journals of the Sponsoring Consortium for Open Access Publishing in Particle Physics (SCOAP^3) where no extra costs occur. In addition, all articles will be posted on the open-access `arXiv` preprint server.

5.1.3 Instrumentation

5.1.3.1 Equipment exceeding € 10,000

Computing. The computing system requires 250 TB storage (48,600 €), where the respective hardware will be provided and operated by GridKa. Furthermore an access server (22,500 €) will be required as primary access point to the analysis facility, including processing power and services for simulations. The estimate for the total cost is **71,100 €** which will be partially covered by KIT: **The KIT Division 5 recognizes the relevance of DELight and supports the proposed RU by providing seed funding covering the costs for the 250 TB storage.**

DAQ hardware. The DAQ system requires 16 bit ADCs to support about 50 readout channels and an FPGA for customized first-level trigger algorithms. Commercial solutions are available, e.g. from CAEN. The open FPGA waveform digitizer family from CAEN includes a 64 channels 16 bit digitizer with an FPGA (Xilinx Zynq UltraScale+) architecture that is accessible, i.e. open, for customization. Such a device enables digital waveform processing and recording of up to 64 independent wafer calorimeters and trigger algorithm customization, which matches the requirements of P5. The cost is **25,500 €**, which will be covered by UHD: **The UHD rectorate recognizes the relevance of DELight and supports the proposed RU by providing seed funding covering the costs for this device.**

5.1.3.2 Major Instrumentation exceeding € 50,000 – Does not apply.

P6 - Science analysis

Applicant: Kathrin Valerius (Karlsruhe)
Co-applicants: Klaus Eitel (Karlsruhe), Christian Enss (Heidelberg), Torben Ferber (Karlsruhe), Loredana Gastaldo (Heidelberg), Felix Kahlhoefer (Karlsruhe), Sebastian Kempf (Karlsruhe), Markus Klute (Karlsruhe), Sebastian Lindemann (Freiburg), Marc Schumann (Freiburg), Belina von Krosigk (Heidelberg)

Project Description

DELight is a new particle physics experiment that can only be realized through the confluence of all six projects. Each project plays a fundamental and unique role, where the project described in the following is responsible for the **high level event building and science analysis**.

Superfluid helium is ideally suited for a Light Dark Matter (LDM) search in nuclear recoils not only by virtue of its low atomic mass which optimizes the signal for LDM particles, but also because the helium target is intrinsically ultra pure and thus basically free of any internal backgrounds, since at mK temperature all impurities freeze out to the boundaries. Hence, provided that external backgrounds from the detector and surrounding materials can be largely suppressed, a very favorable signal-to-background ratio is expected for DELight.

Potential LDM signals in DELight are composed of multiple signatures. This project will perform a detailed study of the energy partitioning among the different signatures present in superfluid helium: phonons & rotons, photons, and long-lived excimers. A detailed understanding of these processes and the response of the detector is vital for utilizing these signatures for discriminating between nuclear recoils and electron recoils. A scheme of calibration measurements will be devised and conducted in close cooperation with P1 and P2, and the pipeline for the analysis of first DM data sets will be set up based on the data format provided by P5. Another important task of project P6 will be to implement the background model worked out jointly with P3 and to study potential spatial dependence of external background components to be suppressed in likelihood analyses.

Within the first funding period of the RU, science data for the DELight phase-I will be acquired and analyzed with an anticipated energy threshold of about 20 eV and an exposure at the kg$\times$d scale, and with the goal to probe new LDM parameter space.

1 Starting Point

State of the art and preliminary work

Superfluid ^{4}He has been considered early on as a unique target material for LDM searches [1, 2] because of its favorable properties and remains a target of interest to date as for example in the HeRALD project using transition edge sensors (TESs) [3]. Extensive studies have been carried out to simulate possible backgrounds and to explore DM sensitivities [3–6] and advanced detection schemes involving field ionization have been proposed [7]. First results have been published recently [8]. All these studies underscore the very promising potential of such a detector.

The DELight experiment is based on the existing concept of a superfluid helium target cell, with the distinction of employing magnetic microcalorimeters (MMCs) for signal sensing. A key feature for efficient event classification in this detector configuration is the presence of three independent and distinguishable signatures and the fact that the energy partitioning among these depends on the ionization density resulting from the initial particle interaction. The initial interaction prompts a cascade of processes eventually terminating with the total energy distributed among the signal channels of ^{4}He (see figure 2) which can be separated according to their arrival time at the MMCs and into which sensor the energy was deposited:The prompt scintillation signal arrives nearly instantaneously with the recoil event itself ($t = 0$ ms) with a pulse rise and fall time determined by the MMC phonon collection within the absorber. The quantum evaporation signal arrives over a broader time after a delay with respect to the UV photons determined by the quasiparticle propagation time. It is mostly collected by the MMCs in the vacuum above the superfluid phase. Triplet excimers have a lifetime of about 13 s and propagate as ballistic molecules at a speed of $\mathcal{O}(1\,\mathrm{m/s})$ through the superfluid. They eventually decay or quench at a wafer calorimeter surface, causing an eV-range energy release that is delayed compared to the quasiparticle and singlet excimer signals. Thus, the quenching of the triplet molecules at ^{4}He interfaces dominates the waveform at late times, although some level of triplet quenching within the recoil track likely will occur earlier. Figure 6.1 denotes a simulated trace for a DELight setup with MMC readout showing the contributions of the prompt scintillation signal (UV - singlet excimers) and the delayed quantum evaporation signal (Quasiparticles). As a simplification, the contribution from long-lived excimers has been ignored.

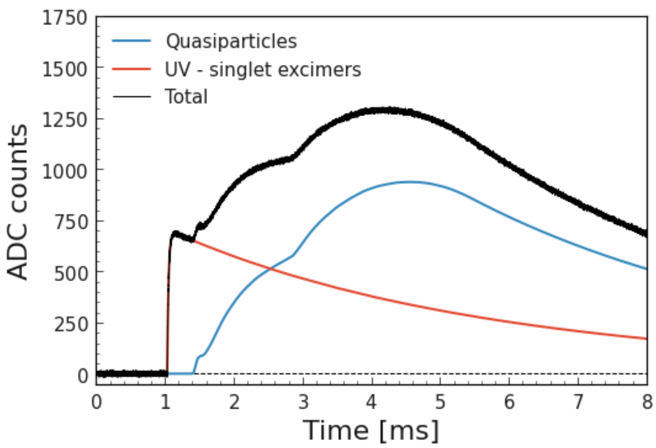

Figure 6.1: Simulated trace (black line) for a 1 keV electronic recoil in a DELight-like setup with MMC readout. The energy is assumed to be equally shared among the three main signatures: quasiparticles (blue), UV photons from singlet excimers (red) and triplets, which are not included in this simulation as they are characterized by long timescales. The simulated signal starts at $t = 1$ ms with the prompt UV component. It is followed by the quasiparticles which have a characteristic time distribution due to the different group velocities of phonons and rotons (parameters based on preliminary results from [3]).

Preliminary work

DELight P6 unites scientific analysis expertise from a broad range of connected fields within particle and astroparticle physics. In setting up the analysis for DELight we draw on methods and tools we developed for experiments and research projects in direct dark matter detection, neutrino physics, high-energy physics, and MMC technology. Our team covers the needs of DELight's full-chain analysis framework from modeling the detector microphysics and incorporating calibration data sets to the interpretation of dark matter science results. In addition to prolific analysis methods and

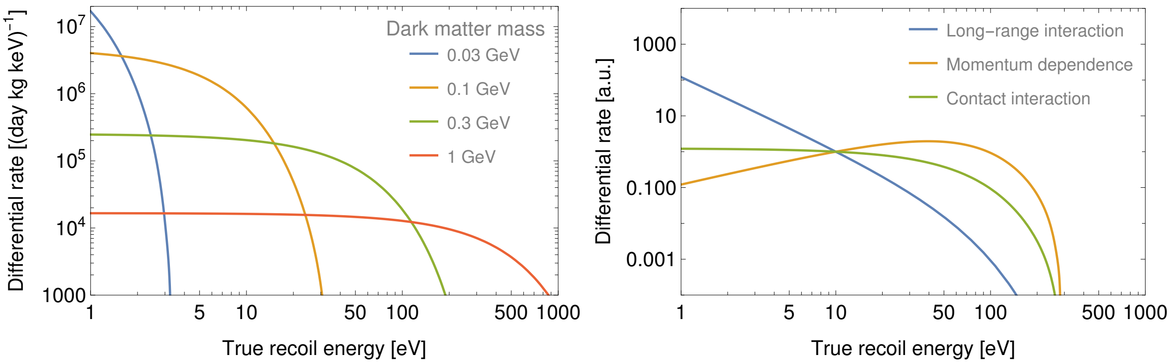

Figure 6.2: Differential LDM event rate as a function of nuclear recoil energy. Left: Contact interaction with a spin-independent DM-proton scattering cross section of $\sigma_p = 1\,\mathrm{pb}$ for different DM masses. Right: Different types of interactions for a DM mass of $m_\chi = 0.3\,\mathrm{GeV}$, normalised to coincide at $E_R = 10\,\mathrm{eV}$.

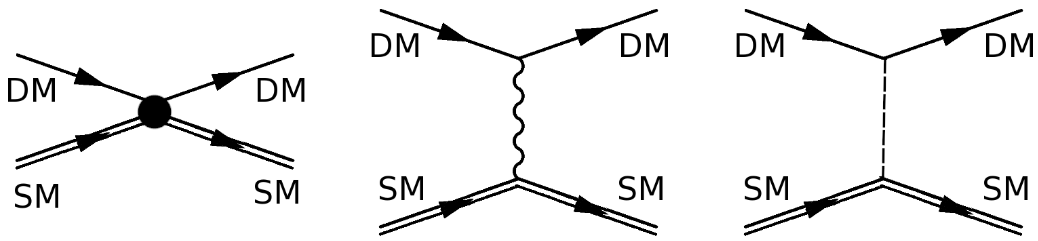

Figure 6.3: Examples of different types of LDM interactions with Standard Model (SM) particles. Left: Commonly assumed contact interactions. Centre: Long-range interactions, arising for example for the exchange of a light dark photon. Right: Non-standard interactions arising from exotic mediators.

computing expertise, our project team also includes a direct link to phenomenology of light dark matter and is thus well poised to address the tasks of setting up the scientific analysis framework for this new experiment along with detailing its near-term and long-term physics reach, for phase-I and beyond. These various preliminary works which all benefit the scientific analysis of DELight in a highly complementary way will be described in the following.

The central ingredient for characterizing expected LDM signals is the differential event rate as a function of nuclear recoil energy. This rate falls rapidly – with steeper slope for smaller DM mass – and has a cut-off at a maximum recoil energy dictated by the assumed velocity distribution of DM particles in the Milky Way halo (figure 6.2, left panel). However, different recoil spectra are possible, for example for the case of long-range or momentum-dependent interactions (figure 6.2, right panel), arising from different types of mediators (figure 6.3). We have many years of experience in calculating these signals for a wide range of DM models, taking into account astrophysical and nuclear uncertainties, and making the theory predictions and likelihoods publicly available [9–11].

An example of full-chain analysis expertise is our comprehensive work on the science analysis for the Karlsruhe Tritium Neutrino experiment (KATRIN). Through the group led by K. Valerius at KIT, our project team has experience that spans from developing the signal and response modeling [12] to full high-level statistical analysis [13] which has been employed to obtain leading results in direct neutrino-mass determination [14] and in kinematic searches for eV- and keV-scale sterile neutrinos [15, 16]. Further, ongoing analyses of KATRIN data comprise the search for light boson emission in beta decay (see, e.g., sensitivity study in [17]), and new physics searches in the framework of general neutrino interactions.

Another example of a full simulation and analysis chain from raw data to the final inference developed in the KIT dark matter group is the analysis of potential supernova (SN) signals in the XENONnT experiment [18] as first described in general in [19]. Here, data-driven signal waveforms were simulated based on SN model neutrino spectra in time and energy and then superimposed to real data streams. An online software trigger was developed to identify SN signals with minimal false alarm rate ready to be integrated into the Supernova Early Warning System (SNEWS) [20]. Based on this trigger, the SN detection sensitivity of XENONnT as well as for DARWIN can be derived as a function of the SN distance.

The SuperCDMS group led by B. v. Krosigk, located both at KIT and UHD, pioneers a highly modular analysis and signal modeling software package approach within SuperCDMS both for LDM and bosonic DM searches [21, 22]. The modular approach allows to easily share the resulting individual packages which other members of the community, including DELight, can simply import as python package. The same open software, community supporting, spirit is planned for DELight, and the P6 project group will be able to build on both the experience and on various of the available python packages, written by members of B. v. Krosigk's group [23–26] as well as on many parts of the XENON data acquisition, processing and analysis tools that are openly available via github [27].

Analysis tools relevant for DELight P6 have been developed in the framework of the ECHo experiment, which, as DELight, is based on the use of MMC arrays. Data reduction algorithms with no or just slight energy dependence have been demonstrated [28] which are of utmost importance for spectral shape analysis. Other data reduction algorithms have also been investigated in relation to studies to identify and suppress background [29, 30]. Simulations to study the sensitivity of the ECHo experiment to a finite neutrino mass are discussed in [31]. A first analysis of the endpoint region of the ^{163}Ho spectrum based on a profile log-likelihood ratio hypothesis test is presented in [32], which led to the first limit on the effective electron neutrino mass from ECHo.

An initial pipeline for the processing and analysis of data acquired using an MMC towards DELight was developed by members of the project team in [33]. This work consists in the systematic study of the MMC traces using an optimum filter (OF) analysis, and led to a world-leading energy resolution for cryogenic X-ray calorimeters.

A preliminary geometry of the first phase of the DELight experiment has already been developed using the GEANT4 framework.The design of the dilution refrigerator is based on commercially available solutions, while the geometry of the detector is flexible and can be easily modified for optimization (see also figure 3.1). Using a simplified geometry, various background sources were already simulated, such as the radiogenic background coming from the material radioactive contamination, both as gamma and neutron radiation. The latter simulation is possible thanks to the implementation of the SaG4n software tool for the simulation of (α, n) reactions [34].

Energy and detector response calibration is a very special challenge for an experiment searching for rare low energy nuclear recoils such as DELight. We have already identified several potential ways to realize a neutron source to fulfill the requirements for DELight phase-I which will be described in more detail in the work package P6.4. This is based on experience from neutron calibration schemes developed for the LZ experiment [35] as well as on dedicated experiments to measure neutron fluxes with very low intensities in underground laboratories [36, 37].

2 Objectives and work programme

2.1 Anticipated total duration of the project

The total duration of this project is fully aligned with the timeline of DELight phase-I as described in Sec. 2.2 of the "Overall Description of the Research Unit and the Coordination Proposal". The anticipated total duration of the project is four years.

2.2 Objectives

This project P6 is an integral part of the overall DELight RU proposal. P6 is responsible for setting up and coordinating the software development and maintenance of a full analysis chain of raw data as recorded by the MMC-based wafer calorimeter array (see projects P5 for raw data and P4 for Slow Control parameters) to final inference analyses in LDM and other physics parameter spaces. As outlined schematically in figure 6.4, the analysis chain is complemented by a simulation branch.

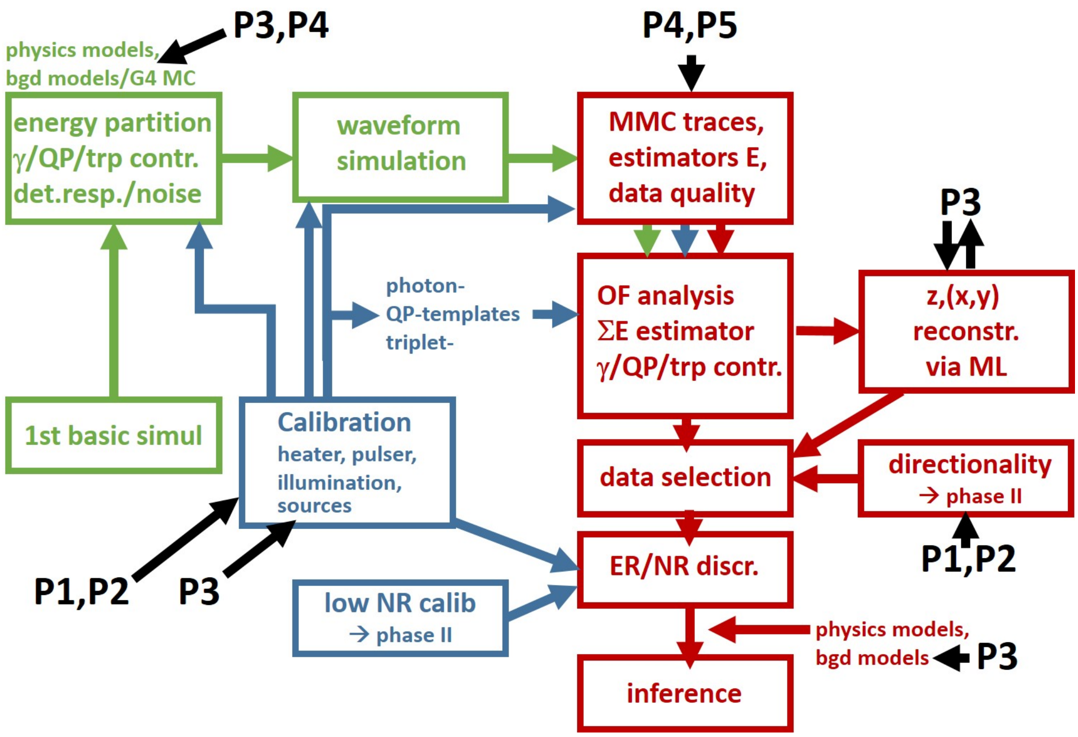

Figure 6.4: Structure of the simulation (green) and analysis (red) pipeline together with the calibration scheme (blue) and the interplay with other projects (black arrows); see text for details.

While the MC simulations in P3 concentrate on modeling energy deposits from various physical sources, here the focus will be on modeling the expected waveforms from each MMC. In the early phase of DELight this allows to feed the analysis software with simulated data in a commissioning phase, but also to develop step-by-step ever more detailed models of MMC waveforms. Major input into both chains is provided by calibration data from integrated heater, pulser and illumination sources as well as radioactive sources.

The timeline of P6's work programme is shown in Fig. 6.5. It also shows the tasks that are equitably performed by all participants of the RU.

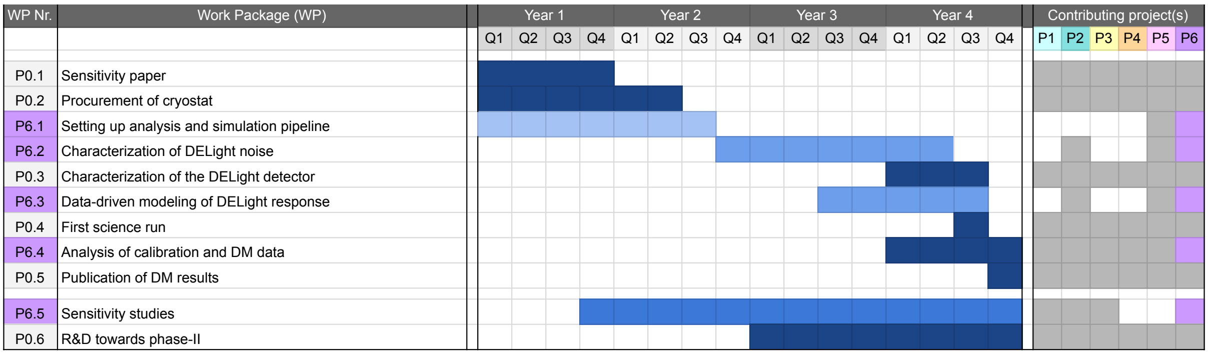

Figure 6.5: Summary of the P6 work programme. The work package (WP) numbers indicate the respective lead project (here P6) and the count within that project's list of WPs. The P0 identifier is used for WPs that are equitably performed by all participants of the RU. The shades of blue within the timeline indicate the amount of contributing projects. The lightest blue is used for WPs only conducted within P6 and one second project. The darkest blue is used for WPs to which all projects P1 - P6 contribute. The rightmost block of the program signals the lead project (color) and the further contributing projects (gray).

The first objective of the physics analysis is a thorough assessment of DELight's sensitivity (work package P0.1). In addition to the projected sensitivity given in figure 1 assuming zero background and a threshold of 20 eV, we will determine realistic background levels or upper limits together with a detailed description of the detection efficiency near threshold based on simulated waveforms as well as input parameters from the wafer calorimeters. Once real data are available, the prime goal of the analysis is to explore new parameter space for LDM via scattering off He nuclei. However, the analysis of the acquired data will allow many other physics channels to be investigated. One example is the DM search utilizing the Migdal effect resulting in observable electronic recoils (see also WP 6.5).

In the following we describe in detail the tasks led by P6.

2.3 Work programme including proposed research methods

The structure of the work programme of the DELight P6 is laid out in figure 6.4, which also illustrates numerous interfaces with the other five projects P1 - P5. The breakdown of P6 into individual work packages is summarized schematically in figure 6.5. The work packages are grouped in two categories: one where P6 leads the respective efforts (P6.1-5) and one where the work packages are equitably performed by all participants of the RU (P0.1-6). The following tasks and milestones were identified to achieve the objectives described above.

P6.1: Setting up the analysis and simulation pipeline

One of the major tasks of DELight project P6 is the development and maintenance of the full analysis software and subsequently the analysis of the acquired data. As indicated in figure 6.4, the raw data will be provided by the data acquisition system (project P5) in form of traces of individual MMC channels together with first estimators of peak amplitudes, as well as data quality information (project P4). A central element is the event builder where signals will be extracted from individual traces based on an optimal filtering analysis. This requires detailed understanding of all detector and system noises which forms the dedicated work package P6.2. The output of this analysis step will be an event description with total energy, individual MMC channel contributions as well as an estimator of the signal composition in terms of prompt scintillation, quasiparticle evaporation and triplet excimer deexcitation derived from the pulse shapes. Based on parameters such as stability of the entire system and trace baselines, data will then be processed and analyzed towards potential signals of LDM or other BSM physics taking into account the discrimination of the event described as electron (ER) or nuclear recoil (NR). In a subsequent step of developing the analysis chain, position information of the event vertex may be obtained where we intend to deploy machine learning (ML) methods already applied in numerous analyses described in section 1. While directionality of the quasiparticle signal has been observed at $\mathcal{O}$ (MeV) scale [38], this has yet to be proven for the low energy region of interest. DELight is ideally suited for dedicated calibration measurements. To derive information of the directionality of the recoil in the superfluid requires a profound understanding of the quasiparticle propagation. A suitable calibration scheme will be developed within this project to explore the potential of directionality in phase-II.

In parallel with the analysis chain, a simulation of the detector response for its different channels will be developed (green part in figure 6.4). During the design phase this work will rely on cross-section measurements and previous publications [39, 40], such as the trace shown in Fig. 6.1. These first simulations are an important input not only for understanding the potential physics reach of the experiment, but also for the development of the DAQ (P5) and algorithms such as for the position reconstruction. Moreover, they are important to estimate the best parameters for the MMC-based wafer calorimeters, especially in terms of time resolution, and drive their design (P2). As data are acquired, the simulated traces can be validated using calibration sources and be adjusted using data-driven inputs. This is a valuable information to understand the microphysics of signal generation in the superfluid helium. The model obtained in this first phase can be used as verified input for the design and simulation of the phase-II of the DELight experiment. To fully model background events from primary energy deposits to MMC waveforms, we will also use the GEANT4 simulation packages with the preliminary design of the cryostat and its materials as detailed in P3.

P6.2: Characterization of DELight noise

As described in P5 and especially its work package P5.6, the raw data as acquired by the DAQ system will be provided with a first-level reconstruction including event details like energy, position and timing information. The offline processing relies significantly on a detailed understanding of the noise in form of power spectral densities (PSDs) for each MMC channel, as they are one important input to an optimal filter (OF) based trace analysis. To achieve this goal, OF algorithms as developed in Ref. [33] for a specific type of MMCs will be adopted. The periodic measurement and characterization of the noise of the detector will ensure optimal results at the analysis level, but it will be also important to monitor changes in the detector conditions. A precise and constantly updated PSD is moreover fundamental for the development of an efficient online trigger as input for P5.

In addition to the online processing, cross correlations of noise in multiple MMC channels will be investigated, thus identifying system-wide noise components of the PSDs and consequently improving the overall system performance. The potential gain coming from the cross correlation of the noise will be initially studied using the simulation framework developed in work package P6.1. The use of simulated traces will allow the further development of the OF-based framework towards a multi-channel analysis. Data acquired with multi-channel R&D projects will be used to validate the tools before the start of data acquisition with DELight, and the final analysis will use the information provided in work package P6.3.

P6.3: Data-driven modeling of DELight response

To identify and analyze signal pulses, signal templates for each MMC channel are required: This implies a signal waveform consisting in general of traces from prompt UV scintillation photons, quasiparticle evaporation and triplet excimer deexcitation, with different contributions depending on whether the MMC is placed above the liquid or immersed in the superfluid. While, in a first step, these templates are purely based on waveform simulations, they will gradually be replaced by proper data-driven templates as schematically outlined in figure 6.4. This transfer to data-driven modeling of signals and thereby of the detector response requires input from dedicated calibration measurements.

P6.4: Analysis of calibration and DM data

Energy and detector response calibration is a very special challenge for DELight as in a low-background measurement, calibration sources can't be permanently mounted in the target volume. On the other hand, the construction of a mechanical system that allows temporarily inserting calibration sources into the cell is very sophisticated as this system must cross the hermetic helium cell and must not bring in a noticeable heat input. For this reason, P2 will implement an *ex-situ/in-situ* calibration scheme. As described there, all wafer calorimeters will be equipped with a microfabricated heater arrangement that allows applying well-defined heater pulses to the absorber. Analysis of these heater pulses requires a measurement prior to an actual science run where radioactive sources will be mounted within the helium cell to determine the length and amplitude of heater pulses that mimic signals as caused by calibration sources. These parameters only depend on the heater resistance, the latter can be checked in-situ during a science run. Detector calibration will be done by regularly applying heater pulses to the individual calorimeters and measuring the signal height. The analysis and monitoring of these regular calibration data in conjunction with data from calibration sources are an indispensable input to the analysis chain of the data acquired in science runs and will constitute a major task of the overall analysis project. As LDM signals are expected at low energies, proper determination of energy resolution and detection efficiency near the detection threshold are required to interpret the data. Cross checks such as low noise conditions, consistency of various data sets in time and between different wafer calorimeters will be performed as a data selection before the final analysis with respect to potential DM signals. An important parameter to distinguish between various signal models as well as to discriminate background is the classification of energy deposits as originating from electronic (ER) or nuclear recoils (NR). Thus, a long-term calibration concept including NR calibration is envisaged.

One of the challenges lies in the precise characterization of the detector response to low-energy NRs, and thus in the implementation of a suitable calibration system. Well-characterized neutron sources are typically employed for this purpose in direct DM detection experiments (a recent overview of technology options is presented in [41]). In order to probe $\mathcal{O}\,(100\,\mathrm{eV})$ nuclear recoil energies with DELight, a low-energy neutron source at $\mathcal{O}\,(10\,\mathrm{keV})$ is needed.

In preliminary studies, we have already identified several potential ways to realize a neutron

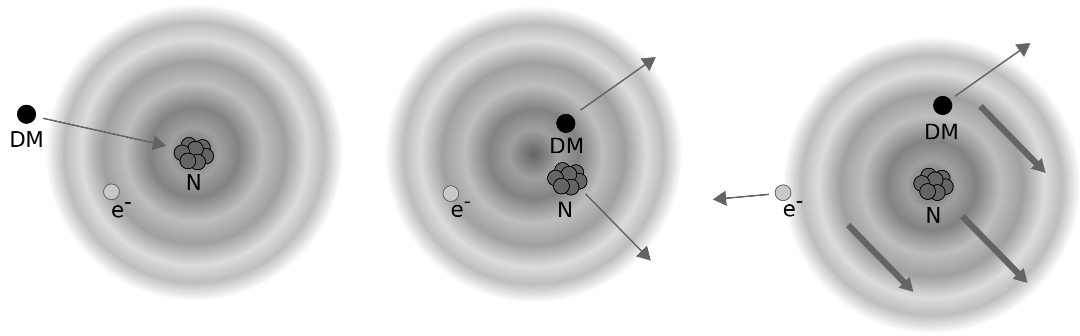

Figure 6.6: Illustration of the Migdal effect. A DM particle scatters off a nucleus, such that it gains momentum relative to its electron cloud. The electron cloud quickly catches up with the nucleus, but individual electrons may become unbound in the process. This gives rise to an observable electronic recoil signal even when the nuclear recoil energy is below threshold.

source to fulfill the requirements for DELight phase-I. Among the candidate concepts under consideration are photoneutron production in ^{124}Sb-^{9}Be (like in the portable monoenergetic neutron source developed for SPICE/HeRALD, [42]), an iron-filtered deuterium-tritium (DT) neutron generator (as discussed for RICOCHET [43] based on the work in [44, 45]), and neutron resonance transmission analysis with a DT generator [46]. In the scope of this work package, P6 will carefully evaluate different options and select the most suitable approach for DELight. In close cooperation with projects P1, P2, P3 and P4 we will develop and realize a calibration concept and set up the necessary software tools to analyze calibration data as a required input for the science analysis of DELight.

P6.5: Sensitivity studies

Once the analysis pipeline has been established, and signal waveforms (within P6) and background models (from P3) are available, the central task of P6 is to perform the statistical analysis, i.e. the inference on a specific hypothesis for LDM or another BSM model. A multitude of methods are available for this purpose, including a cut-and-count method (in case of sufficient separation of signal and background), profile likelihood ratios [47] (for signals and background that differ in shape) and the optimum interval method [48], which allows setting a conservative exclusion limit in case some events are observed without the necessity to have a specific background model.

While these methods will primarily be applied to constrain the cross section of LDM scattering off nuclei as a function of the LDM mass, it will be exciting to exploit alternative physics channels of superfluid helium detectors which could be enabled by DELight's low energy threshold. One such example are neutrinos originating either from the sun or from supernovae, which may coherently scatter off nuclei and give rise to signals that resemble LDM scattering [49]. Detecting such signals may not only serve to constrain the neutrino flux, but would also enable searches for non-standard neutrino interactions [50]. In preparation for phase-II of DELight, it will also be interesting to study the ability of superfluid helium detectors to probe new physics through electron recoils, produced either through direct scattering (of LDM or neutrinos) or via the so-called Migdal effect [51, 52], see figure 6.6. We will explore the necessary detection techniques, calibration measurements and background models in order to obtain first sensitivity estimates.

In view of the long-term prospects of the superfluid helium technology for LDM searches, it will be essential to understand the complementarity with different direct detection experiments. Given that many of the strongest constraints on LDM stem from experiments searching for scattering off electrons, we will examine the correlations between nuclear and electron recoil signals for different LDM models, such as the ones depicted in figure 6.3. The goal is to compare the strength of various constraints in terms of the underlying model parameters, and to identify models that are dominantly (or even uniquely) constrained by nuclear recoil searches. At the same time it will be highly interesting to study whether the low-energy excesses reported by various direct detection experiments [53] can be excluded in a model-independent way.

P0.1-6: Procurement of cryostat, detector characterization, first science data, DELight publications, R&D towards phase-II

The work packages P0.1-6 have no leading project but are equitably performed by all participants of the RU. They are an expression of collaboration within the entire RU and thrive on the strong synergies between the projects. The activities of the RU during phase-I of DELight are framed by two main publications, a sensitivity paper (P0.1) at the beginning of the funding period and the publication of the first science results (P0.5) at the end of the funding period. These publications require input from all projects and expertise from all members of the RU and will help shape the science output of DELight. Several additional publications are planned to be published within the funding period. The cryostat is part of the coordination project and its procurement (P0.2) will be carried out by the RU together, just like the characterization of the whole DELight detector (P0.3) and the DELight operations and monitoring of the data taking during the first science run (P0.4). In parallel to phase-I, the RU will jointly start R&D towards phase-II (P0.6). A few key contributions of P6 will be highlighted in the following.

Sensitivity paper. The science reach of the DELight experiment will be detailed in a sensitivity paper early on in phase-I. All six DELight projects will contribute essential parts of the publication, such as the outline of design considerations, experimental concepts for cell, detector and read-out systems, calibration scheme, and analysis chain. Project P6 will lead the description of the physics analysis of DELight, including the background and physics models and inference methods applied for sensitivity estimation.

Characterization of cell and detector system. A thorough characterization of the target cell and MMC-based wafer calorimeter system will be crucial for the timely conduction of the first science run of DELight. Project P6 will contribute to this effort by inspecting the wafer calorimeter signals in close relation with P2 and P5, by assessing the data quality during commissioning runs and developing data selection criteria, as well as by studying systematic effects induced by individual system components and those present in the combined signal production chain.

First science run and data analysis. The primary goal of DELight phase-I is to obtain high-quality first science data which allow probing as yet unexplored LDM parameter space. This goal can be achieved with a comparably short data-taking campaign yielding an initial exposure of $\mathcal{O}(\mathrm{kg{\cdot}d})$ at an energy threshold around 20 eV. With the high-level event building, analysis and inference pipeline developed chiefly within P6, this project will make essential contributions to realizing the first physics results of DELight.

Development of DELight towards phase-II. A key asset of the DELight concept is that it promises to deliver groundbreaking physics output in a moderate-scale first project phase, while offering further scalability and increased physics reach in subsequent extensions of the experiment. Next to ensuring the physics analysis and scientific harvest of phase-I, project P6 will invest substantial efforts in the exploration of a potential phase-II of DELight, producing projections on improved LDM sensitivity as well as for other intriguing physics cases. This work will be carried out in close cooperation of experimentalists and phenomenologists on the project team, to ascertain that an ambitious, but realistically viable scientific programme is set up. To this end, P6 will evaluate the system performance of DELight phase-I and gather input from all other DELight projects regarding the required improvements of the experimental configuration in phase-II which goes beyond a mere increase of target volume and exposure, in particular in view of background suppression.

2.4 Handling of research data

The same text applies as in Sec. 2.3 of the "Overall Description of the Research Unit and the Coordination Proposal".

2.5 Relevance of sex, gender and/or diversity

Sex and/or gender is not relevant to the research project. Though we strive for a diverse group of researchers, the level of diversity is also not relevant to the research project.

3 Project- and subject-related list of publications

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[62] F. Abudinén *et al.*, "Search for $B^+ \to K^+ \nu \nu^-$ Decays Using an Inclusive Tagging Method at Belle II," *Phys. Rev. Lett.*, vol. 127, no. 18, p. 181802, 2021. doi: 10.1103/PhysRevLett.127.181802

[63] S. Chatrchyan *et al.*, "Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC," *Phys. Lett. B*, vol. 716, pp. 30–61, 2012. doi: 10.1016/j.physletb.2012.08.021

[64] S. Chatrchyan *et al.*, "Observation of a New Boson with Mass Near 125 GeV in *pp* Collisions at $\sqrt{s} = 7$ and 8 TeV," *J. High Energy Phys.*, vol. 06, p. 081, 2013. doi: 10.1007/JHEP06(2013)081

[65] F. Abudinén *et al.*, "Search for Axion-Like Particles produced in e^+e^- collisions at Belle II," *Phys. Rev. Lett.*, vol. 125, no. 16, p. 161806, 2020. doi: 10.1103/PhysRevLett.125.161806

[66] A. M. Sirunyan *et al.*, "Evidence for Higgs boson decay to a pair of muons," *J. High Energy Phys.*, vol. 01, p. 148, 2021. doi: 10.1007/JHEP01(2021)148

[67] CMS collaboration, "A portrait of the Higgs boson by the CMS experiment ten years after the discovery," *Nature*, vol. 607, no. 7917, pp. 60–68, 2022. doi: 10.1038/s41586-022-04892-x

4 Supplementary information on the research context

4.1 Ethical and/or legal aspects of the project

4.1.1 General ethical aspects

We do not anticipate any risks and/or harm to individuals or groups or the environment and/or the potential for other negative effects that might be posed by our research.

4.2 Employment status information

Last name: Valerius
First name: Kathrin
Employment status: Full professor (W3) at the Karlsruhe Institute of Technology

4.3 First-time proposal data – Does not apply.

4.4 Composition of the project group

K. Valerius, K. Eitel, S. Lindemann, and M. Schumann have a track record of direct DM search analyses with cryogenic noble gas detectors [54–57]. K. Eitel and B. v. Krosigk are experts in direct LDM search analyses with an ultra-low energy threshold [21,22,47,58]. B v. Krosigk was the Analysis Coordinator of SuperCDMS from 2018 to 2020. M. Schumann was the Analysis Coordinator of XENON from 2010 to 2013. All aforementioned applicants are long-standing members of world-leading rare-event search experiments and specifically of the direct DM search experiments XENON (K. Valerius, K. Eitel, S. Lindemann, M. Schumann, F. Toschi), DARWIN (K. Valerius, K. Eitel, S. Lindemann, M. Schumann, F. Toschi, B. v. Krosigk), EDELWEISS (K. Eitel) and SuperCDMS (B. v. Krosigk). Our project team furthermore benefits from extensive experience in operation, read-out, data processing and science analysis of wafer calorimeter arrays in the ECHo experiment

Table 6.1: Individuals who will work on the project but will not be paid out of the project funds.

Name and academic title	Employment status	Institution	Type of funding
	Paid by institution		
Prof. Dr. Kathrin Valerius	Full professor (W3)	KIT	institutional
Dr. Klaus Eitel	Staff scientist	KIT	institutional
Prof. Dr. Christian Enss	Full professor (C4)	UHD	institutional
Prof. Dr. Torben Ferber	Full professor (W3)	KIT	institutional
PD Dr. Loredana Gastaldo	Staff scientist	UHD	institutional
Prof. Dr. Felix Kahlhoefer	Tenure-track professor (W1→W3)	KIT	institutional
Prof. Dr. Sebastian Kempf	Full professor (W3)	KIT	institutional
Prof. Dr. Markus Klute	Full professor (W3)	KIT	institutional
Dr. Sebastian Lindemann	Staff scientist	UFR	institutional
Prof. Dr. Marc Schumann	Full professor (W3)	UFR	institutional
Prof. Dr. Belina von Krosigk	Full professor (W3)	UHD	institutional
	Paid by third-party		
Dr. Benedikt Maier	Post-doctoral researcher	KIT	Alexander von Humboldt Foundation
Dr. Francesco Toschi	Post-doctoral researcher	KIT & UHD	German Research Foundation (DFG)

(L. Gastaldo, Ch. Enss, S. Kempf). K. Valerius has wide-ranging experience in analysis methods and simulation tools as a member of the Analysis Coordination Group of the KATRIN experiment [12–14]. F. Kahlhoefer is a leading proponent in the field of DM calling for a close collaboration between experimentalists and theorists in order to define benchmark models, optimize experimental sensitivity and facilitate the reinterpretation of results [59]. In particular, he has worked on the response of direct detection experiments to sub-GeV DM [52, 60] and on the reconstruction of DM model parameters from data [10, 11]. T. Ferber was the Belle II physics performance coordinator from 2019 to 2021 and has established the Belle II capability to deliver world-leading physics results [61, 62]. M. Klute played a central role in CMS data analyses resulting in the discovery of the Higgs boson [63, 64]. Both are renowned experts in beyond standard model physics and in state-of-the-art analysis techniques with a track record of path-breaking analysis results [65–67]. B. Maier and F. Toschi are lead authors of a study which presents a powerful MMC analysis pipeline based on optimum filtering [33]. This work, which demonstrates unprecedented energy resolution in an MMC, lays an important foundation for the analysis framework of DELight.

4.5 Researchers in Germany with whom you have agreed to cooperate on this project – Does not apply.

4.6 Researchers abroad with whom you have agreed to cooperate on this project – Does not apply.

4.7 Researchers with whom you have collaborated scientifically within the past three years

All respective researchers are included in Sec. 5.7 of the overall description.

4.8 Project-relevant cooperation with commercial enterprises – Does not apply.

4.9 Project-relevant participation in commercial enterprises – Does not apply.

4.10 Scientific equipment

Computing infrastructure

Computing capacity is a key factor in the timely progress and successful completion of project P6. Software development and computing tasks including batch jobs as well as interactive jobs will be supported through computing infrastructure at various levels:

- KIT's Institute for Astroparticle Physics (IAP) and the Institute of Experimental Particle Physics (ETP) operate local computing clusters to which members of the P6 project team have managing access. Simulation data as well as measurement data from the DELight experiment (commissioning/calibration runs and science runs) can be stored locally; for larger data volumes we plan to rent disk space at GridKA (`https://www.scc.kit.edu/en/research/gridka.php?`). A budget request for storage space and for an upgrade of the local analysis computing platform is foreseen within the DELight project P5 "Data acquisition and computing".
- Centrally managed resources are available on request at the bwUniCluster_2.0 at KIT (`https://www.scc.kit.edu/en/services/bwUniCluster_2.0.php`) and at the bwForCluster NEMO at the University of Freiburg (`https://www.nemo.uni-freiburg.de`).
- For potentially increased computing demands in a future stage of DELight, project researchers are eligible to apply for resources at HoReKa (`https://www.scc.kit.edu/en/services/horeka.php`).

4.11 Other submissions – Does not apply.

4.12 Other information – Does not apply.

5 Requested modules/funds

5.1 Basic Module

5.1.1 Funding for Staff

The following staff is requested for the successful completion of this project within DELight:

- **0.5 Postdoctoral Researcher for 4 yrs:** One full-time (100%) postdoctoral researcher with a degree in experimental (astro)particle physics, ideally with previous experience in DAQ and trigger systems as well as computing, will be hired at KIT or UHD for the full funding period and will be equally shared between projects P5 and P6. This position situated at the intersection of the two DELight projects is motivated by the benefit of combined expertise and understanding of the trigger and first-level reconstruction together with the analysis demands to achieve a high DM sensitivity. Within this project P6, the postdoctoral researcher will thus be in charge of the essential interface between the first-level reconstruction of detector signals and the subsequent higher-level analysis. In the beginning of the project the main tasks lie in work package P6.1 (set-up of analysis pipeline), whereas the focus later shifts to P6.2 (characterization of MMC array noise) and P6.3 (modeling of detector response). For the creation of the overall analysis pipeline, the postdoctoral researcher will have a leading role and will coordinate the contributions and inputs from adjacent DELight projects. The postdoctoral researcher will supervise the doctoral researcher working on P6.
  According to the DFG Personnel Rates for 2023 we expect annual costs of 40,050 €/year for half of the 100% TV-L E13 position, summing up to **160,200 €** in total.

- **1 Doctoral Researcher for 4 yrs:** One doctoral researcher, ideally with a background in experimental (astro-)particle physics, will be hired for the full funding period. Four years are an adequate duration to obtain a doctoral degree in experimental particle physics which includes setting up a new experiment. The duration of four years will allow the doctoral researcher to participate in the full development cycle of the DELight analysis framework from its very conception up to the harvest of first science results.
  At the outset of the PhD project, the central task of the doctoral researcher will lie in simulation work to generate the physics and detector models and to collect the required inputs from P3 and P4. On the technical side, the project includes the conception and implementation of a calibration system (in close cooperation with the doctoral researchers working in P2 and with input and support from P3, see WP 3.1) and the preparation of the analysis pipeline to receive calibration data. Based on the characterization of the detector performance the sensitivity studies for the first phase of DELight will be updated in the course of the doctoral project. Finally, the doctoral researcher will participate in data-taking for the first science run of DELight and in producing initial analysis results for the LDM search.
  According to the DFG Personnel Rates for 2023 we expect annual costs of 55,575 €/year for the 75% TV-L E13 position, summing up to **222,300 €** in total.

5.1.2 Direct Project Costs

5.1.2.1 Equipment up to € 10,000, Software and Consumables

Computing infrastructure: See funds requested in project P5 (Data acquisition and computing). No separate computing budget is foreseen for this project P6 (Science analysis).

5.1.2.2 Travel Expenses

For DELight Project 6 a total of **15,200 €** travels funds are required to cover the following costs:

- **International conferences.** The attendance of and contribution to relevant international conferences, like IDM (the International Conference on the Identification of Dark Matter), LDW (Meeting of the Light Dark World International Forum), TAUP (the International Conference on Topics in Astroparticle and Underground Physics), LTD (the International Workshop on Low-Temperature Detectors) or LIDINE (LIght Detection In Noble Elements), provides important visibility, networking, and interpersonal communication opportunities strengthening DELight and the careers of its scientists. We estimate the cost for a typical 5 day long international conference or workshop at 1500 € and foresee travels to 4.5 conferences in the 4 years funding period. (0.5 trips indicate that the other half is funded by DELight Project 5.) The total amount required is thus **6800 €**.

- **DPG Spring Meetings.** Doctoral and postdoctoral researchers, as well as the DELight project which they represent, strongly benefit from attending the annual Spring Meeting of the DPG (German Physical Society) every year. Especially doctoral researchers use this opportunity for their first presentations to the wider scientific community. We estimate the costs for a 5 day long trip to the DPG Spring Meeting at a German city at 1000 € and plan with six trips during the funding period, which amounts to **6000 €**.

- **DELight in-person meetings.** This project is tightly connected to other DELight projects (e.g., P1 – cryogenic setup and ^{4}He cell, P2 – MMC detectors, P3 – Low-background environment and P5 – Data acquisition and computing), which requires close coordination with our colleagues. This requires occasional travel to the other institutions for day-long in-person meetings. Here we can clearly benefit from the close geographical proximity of the three DELight institutions. We estimate the average costs for a short trip at 150 € and anticipate four short trips per year. This amounts to **2400 €** in total. (The costs for traveling to or hosting the two in-person collaboration meetings per year are covered by the Coordination Project.)

5.1.2.3 Visiting Researchers (excluding Mercator Fellows)

Does not apply. Short-term visits of external researchers are anticipated; these can be covered by the applicant's institutional funds and are eligible for support through the KIT Center Elementary Particle Physics and Astroparticle Physics (KCETA)[7] and its associated graduate school KSETA. Dedicated support measures can be accessed by early-career researchers through the Karlsruhe House of Young Scientists (KHYS)[8].

5.1.2.4 Other Costs – Does not apply.

5.1.2.5 Project-related Publication Expenses

Does not apply. Project-related publications will be published in journals of the Sponsoring Consortium for Open Access Publishing in Particle Physics (SCOAP^3) where no extra costs occur. In addition, all articles will be posted on the open-access `arXiv` preprint server.

[7] https://www.kceta.kit.edu/english
[8] https://www.khys.kit.edu/english

5.1.3 Instrumentation

5.1.3.1 Equipment exceeding € 10,000 – Does not apply.

5.1.3.2 Major Instrumentation exceeding € 50,000 – Does not apply.

8 CVs of participating researchers

Prof. Dr. Christian Enss

Prof. Dr. Sebastian Kempf

Prof. Dr. Belina von Krosigk

Dr. Sebastian Lindemann

Prof. Dr. Marc Schumann

Prof. Dr. Kathrin Valerius

Curriculum Vitae: Prof. Dr. Christian Enss

Personal Data

Title	Prof. Dr.
First name	Christian
Name	Enss
Current position	Professor of Experimental Physics
Current institution(s)/site(s), country	Heidelberg University, Germany
Identifiers/ORCID	0009-0004-2330-6982

Qualifications and Career

Stages	**Periods and Details**
Degree program	1988 Physics, Diploma, Heidelberg University
Doctorate	1991 Prof. Dr. S. Hunklinger, *Untersuchung der Dynamik von Tunnelsystemen in Gläsern und kristallinen Defektsystemen*, Heidelberg University
Stages of academic/ professional career	since 2004 Full Professor (C4), Heidelberg University 2002-2004 Associate Professor, Brown University (USA), 2001-2002 Professor Konstanz University (temporary stand in) 1999-2001 Lecturer, Heidelberg University 1998-1999 Professor, Bayreuth University (temporary stand in) 1996-1997 Lecturer, Heidelberg University 1994-1995 Reserach Associate, Heidelberg University 1992-1993 Postdoctoral Fellow, Brown University (USA)

Supplementary Career Information

none

Activities in the Research System

Selected activities

since 2022	Coordinator of the BMBF project SuperLSI
Since 2020	Head of the Section "Cryogenic Detectors and Superconducting Electronics" at the Institute for Data Processing and Electronics, KIT
Since 2018	Chair of the Low Temperature Section of the German Physical Society
2017	Chair of the international Conference on Ultralow Temperature Physics ULT-2017
2017	Chair of the Panel for Evaluation of Science in Estonia 2012 - 2017
2015 – 2017	Chair of the int. committee of Low Temperature Detector Conference Series
Since 2016	Coordinator of Advanced Cryogenic Summer Schools "Cryocourse"
Since 2016	Chair of the Low Temperature Section and member of the Condensed Matter Division board of the European Physical Society
Since 2015	Series Editor Condensed Matter Physics, DeGruyter
Since 2015	Spokesperson of the DFG Research Unit FOR2202 - ECHo
Since 2014	Coordinator of the European Microkelvin Platform
2011 – 2012	Chair of the panel for the evaluation of physics in Finland 2007 - 2011
2009 – 2011	Chair of the Faculty for Physics and Astronomy at Heidelberg University
2011	Chair of the 14th International Workshop on Low Temperature Detectors
Since 2005	Member of the int. advisory board of the Low Temperature Conference Series

Scientific Results

Category A

1. T. Sikorski *et al.*, "Measurement of the ^{229m}Th isomer energy with magnetic microcalorimeter", *Phys. Rev. Lett.* 125, 142503 (2020), doi: 10.1103/PhysRevLett.125.142503.
   personal contribution: contributing author, experiment was carried out by my group, supervision of students.

2. A. Fleischmann, A. Reiser, C. Enss, "Noise Thermometry for Ultralow Temperatures", *J. Low Temp. Phys.* 201, 803 (2020), doi: https://doi.org/10.1007/s10909-020-02519-x.
   personal contribution: lead author.

3. P.C-O. Ranitzsch *et al.*, "Characterization of the ^{163}Ho spectrum; A step towards the electron neutrino mass determination", *Phys. Rev. Lett.* 119, 122501 (2017), doi: 10.1103/PhysRevLett.119.122501.
   personal contribution: contributing author, experiment was carried out by my group, supervision of students.

4. S. Eliseev, *et al.*, "Direct Measurement of the Mass Difference of ^{163}Ho and ^{163}Dy Solves the Q-Value Puzzle for the Neutrino Mass Determination", *Phys. Rev. Lett.* 115, 062501 (2015), doi: 10.1103/PhysRevLett.115.062501.
   personal contribution: contributing author, part of the experiments was carried out by my group, supervision of students.

5. M. Bartkowiak, M. Bazrafshan, C. Fischer, A. Fleischmann, C. Enss, "Nuclear Quadrupole Moments as a Microscopic Probe to Study the Motion of Atomic Tunneling Systems in Amorphous Solids", *Phys. Rev. Lett.* 110, 205502 (2013), doi: 10.1103/PhysRevLett.110.205502.
personal contribution: lead author, experiment was carried out by my group, supervision of students.

6. J. Schindele, A. Reiser, and C. Enss, "Fluctuation-dissipation theorem in liquid and glassy glycerol: Frequency dependent dielectric permittivity and dielectric polarization fluctuation measurements", *Phys. Rev. Lett.* 107, 095701 (2011), doi: 10.1103/PhysRevLett.107.095701.
personal contribution: lead author, experiment was carried out by my group, supervision of student.

7. A. Würger, A. Fleischmann, C. Enss, "Dephasing of Atomic Tunneling by Nuclear Quadrupoles", *Phys. Rev. Lett.* 89, 237601 (2002), doi: 10.1103/PhysRevLett.89.237601.
personal contribution: contributing author, contributing to model development.

9. P. Strehlow, C. Enss, S. Hunklinger, "Evidence for a Phase Transition in Glasses at Very Low Temperatures - A Macroscopic Quantum State of Tunneling Systems?", *Phys. Rev. Lett.* 80, 5361 (1998), doi: 10.1103/PhysRevLett.80.5361.
personal contribution: local coordination, my group lead the analysis and the publication.

9. C. Enss, S. Hunklinger, "Incoherent Tunneling in Glasses at Very Low Temperatures", *Phys. Rev. Lett.* 79, 2831 (1997), doi: 10.1103/PhysRevLett.79.2831.
personal contribution: lead author, contribution to model development and conducting the simulations.

10. HERON collaboration, "Angular Distribution of Rotons Generated by Alpha Particles in Superfluid Helium: A Possible Tool for Low Energy Particle Detection", *Phys. Rev. Lett.* 74, 3169 (1995), doi: 10.1103/PhysRevLett.74.3169.
personal contribution: contributing author, participation in building up the experiment.

Category B

1. L. Gastaldo *et al.*, "The Electron Capture in ^{163}Ho Experiment - ECHo", *Eur. Phys. J. Special Topics* 226, 1623 (2017), doi: 10.1140/epjst/e2017-70071-y.
personal contribution: contributing author, project supervision.

Academic Distinctions

Since 2016	Member of the Finish Academy of Science and Letter
1992 – 1993	Feodor Lynen fellow, Brown University (USA)

Other Information

since 2022	Member of the DELight collaboration *DELight is a proposed experiment using superfluid He to search for light DM.*
since 2016	Member of the AMoRE collaboration *AMoRE is dedicated to the search for neutrinoless double beta decay of ^{100}Mo.*
since 2014	Member of the SPARC collaboration *SPARC investigates the atomic physics of highly charged ions.*
since 2014	Spokesperson of the European Microkelvin Platform (EMP) *EMP is a joint European ultralow temperature lab with 17 partners.*
since 2011	Member of the ECHo collaboration *ECHo is dedicated to the direct determination of the neutrino mass.*
since 2008	Founder and co-owner of Stella Nova Entertainment *Stella Nova Entertainment is a company devoted to science education and public outreach.*

Data protection and consent to the processing of optional data

If you provide voluntary information (marked as optional) in this CV, your consent is required. Please confirm your consent by checking the box below.

☒ **I expressly consent to the processing of the voluntary (optional) information, including "special categories of personal data" in connection with the DFG's review and decision-making process regarding my proposal.** This also includes forwarding my data to the external reviewers, committee members and, where applicable, foreign partner organisations who are involved in the decision-making process. To the extent that these recipients are located in a third country (outside the European Economic Area), I additionally consent to them being granted access to my data for the above-mentioned purposes, even though a level of data protection comparable to EU law may not be guaranteed. For this reason, compliance with the data protection principles of EU law is not guaranteed in such cases. In this respect, there may be a violation of my fundamental rights and freedoms and resulting damages. This may make it more difficult for me to assert my rights under the General Data Protection Regulation (e.g. information, rectification, erasure, compensation) and, if necessary, to enforce these rights with the help of authorities or in court.

I may **revoke** my consent in whole or in part at any time – with effect for the future, freely and without giving reasons – vis-à-vis the DFG (postmaster@dfg.de). The lawfulness of the processing carried out up to that point remains unaffected. Insofar as I transmit "special categories of personal data" relating to third parties in this CV, I confirm that the necessary legitimation under data protection law exists (e.g. based on consent).

I have taken note of the DFG's Data Protection Notice relating to research funding, which I can access at www.dfg.de/privacy_policy and I will forward it to such persons whose data the DFG processes as a result of being mentioned in this CV.

Curriculum Vitae: Prof. Dr. Sebastian Kempf

Personal Data

Title	Prof. Dr.
First name	Sebastian
Name	Kempf
Current position	Professor for Micro- and Nanoelectronic Systems
Current institution(s)/site(s), country	Karlsruhe Institute of Technology, Germany
Identifiers/ORCID	0000-0002-3303-128X

Qualifications and Career

Stages	**Periods and Details**	
Degree program	2007	Diploma in Physics, Heidelberg University, Germany
Doctorate	2012	Prof. Dr. C. Enss, *Entwicklung eines Mikrowellen-SQUID-Multiplexers auf der Grundlage nicht-hysteretischer rf-SQUIDs zur Auslesung metallischer magnetischer Kalorimeter*, Heidelberg University, Germany
Stages of academic/ professional career	since 2020	Full Professor (W3), KIT, Germany
	2018-2020	Senior scientist (tenured), Heidelberg University, Germany
	2014-2018	Postdoctoral researcher, Heidelberg University, Germany
	2013	Visiting scientist, Physikalisch-Technische Bundesanstalt (PTB), Berlin, Germany
	2012	Postdoctoral researcher, Heidelberg University, Germany

Supplementary Career Information

none

Activities in the Research System

selected activities:

since 2023	Member of the Council for Research and the Promotion of Young Scientists (CRYS), Karlsruhe Institute of Technology, Germany
since 2023	Deputy spokesperson of the Karlsruhe School of Elementary Particle and Astroparticle Physics (KSETA), Karlsruhe Institute of Technology, Germany
since 2023	Scientific Director of the Centre for Fabrication and Characterization of High-resolution Superconducting Sensors (HSS), KIT, Germany
since 2022	Co-opted faculty member (Department of Physics), KIT, Germany
since 2022	Member of the International Advisory Committee of the biannual *International Workshop on Low Temperature Detectors*
since 2020	Steering committee of the Karlsruhe Center for Optics and Photonics (KCOP)
since 2020	Member of the division council (Divison III - Mechanical and Electrical Engineering), KIT, Germany
since 2020	Member of the faculty council (Faculty for Electrical Engineering and Information Technology), Karlsruhe Institute of Technology, Germany
since 2020	Member of the Executive Board and Admission Panel of KSETA
since 2020	Member of the Steering Committee of the KIT Center Elementary Particle and Astroparticle Physics (KCETA), Karlsruhe Institute of Technology, Germany
since 2020	Member of the Academic Committee of the Helmholtz International Research School for Astroparticle Physics and Enabling Technologies (HIRSAP)
since 2019	Member of the scientific advisory committee of the annual *Workshop on cryoelectronic devices*
2019	Co-chair of the *First International Workshop on Physics and Applications of Metallic Magnetic Calorimeters*, Heidelberg, Germany
2018	Principal member of the local organization committee of the *Workshop on Cryoelectronic devices - KRYO2018*, Heidelberg, Germany

Scientific Results

Category A

1. J. Geria, ... , S. Kempf, ... and A. Etchegoyen, *Suitability of magnetic microbolometers based on paramagnetic temperature sensors for CMB polarization measurements*, J. Astron. Telesc. Instrum. Syst. 9 (2023) 016002, doi: 10.1117/1.JATIS.9.1.016002.
personal contribution: contributing author, supervisor of PhD student, theory support.

2. M. Wegner, C. Enss and S. Kempf, *Analytical model of the readout power and SQUID hysteresis parameter dependence of the resonator characteristics of microwave SQUID multiplexers*, Supercond. Sci. Technol. 35 (2022) 075011, doi: 10.1088/1361-6668/ac6d15.
personal contribution: contributing author, supervisor of PhD student, theory support.

3. C. Schuster, M. Wegner, C. Enss and S. Kempf, *Flux ramp modulation based hybrid microwave SQUID multiplexer*, Appl. Phys. Lett. 120 (2022) 162601, doi: 10.1063/5.0087994.

personal contribution: contributing author, leading PI of activity.

4. D. Richter, ... L. Hoibl, T. Wolber, N. Karcher, A. Fleischmann, C. Enss, M. Weber, O. Sander and S. Kempf, *Flux ramp modulation based MHz frequency division dc-SQUID multiplexer*, Appl. Phys. Lett. 118 (2021) 122601, doi: 10.1063/5.0044444.
personal contribution: contributing author, leading PI of activity.

5. T. Sikorski, ... , S. Kempf, and A. Fleischmann, *Measurement of the ^{229}Th isomer energy with magnetic microcalorimeter*,
Phys. Rev. Lett. 125 (2020) 142503, doi: 10.1103/PhysRevLett.125.142503.
personal contribution: contributing author, support of detector fabrication.

6. S. Kempf, ... and C. Enss, *Physics and Applications of Metallic Magnetic Calorimeters*, J. Low. Temp. Phys. 193 (2018) 365-379, doi: 10.1007/s10909-018-1891-6.
personal contribution: leading PI of "detector readout" and "fabrication technology".

7. P. C-O. Ranitzsch, ... , S. Kempf, and K. Johnston, *Characterization of the ^{163}Ho electron capture spectrum: A step towards the electron neutrino mass determination*,
Phys. Rev. Lett. 119 (2017) 122501, doi: 10.1103/PhysRevLett.119.122501.
personal contribution: responsible for detector fabrication, contribution to analysis.

8. S. Kempf, ... and C. Enss, *Design, fabrication and characterization of a 64 pixel metallic magnetic calorimeter array with integrated, on-chip microwave SQUID multiplexer*,
Supercond. Sci. Technol. 30 (2017) 065002, doi: 10.1088/1361-6668/aa6d17.
personal contribution: main author, supervision of students, responsible for device design, characterization and data analysis.

9. S. Kempf, A. Ferring and C. Enss, *Towards noise engineering: Recent insights in low-frequency excess flux noise of su-perconducting quantum devices*,
Appl. Phys. Lett. 109 (2016) 162601, doi: 10.1063/1.4965293.
personal contribution: main author, supervision of students, data analysis coordinator.

10. S. Kempf, A. Ferring, A. Fleischmann and C. Enss, *Direct-current superconducting quantum interference devices for the readout of metallic magnetic calorimeters*, Supercond. Sci. Technol. 28 (2015) 045008, doi: 10.1088/0953-2048/28/4/045008.
personal contribution: main author, supervisor of contributing PhD student, responsible for device design, characterization and data analysis.

Category B

1. M. Krantz, ... S. Kempf, *Magnetic microcalorimeter with paramagnetic temperature sensors and integrated dc-SQUID readout*, arXiv:2310.08698 [inst-det] (2023),
doi:10.48550/arXiv.2310.08698. *submitted to Appl. Phys. Lett. for publication.*
personal contribution: main author, leading PI of activity, PhD supervisor.

2. F. Toschi, ... S. Kempf et al., *Optimum filter-based analysis for the characterization of a high-resolution magnetic microcalorimeter towards the DELight experiment*, arXiv:2310.08512

[hep-ex] (2023), doi:10.48550/arXiv.2310.08512. *submitted to Phys. Rev. D for publication. personal contribution: contributing author, contribution to data analysis and interpretation.*

3. C. Schuster and S. Kempf, *Superconducting microcalorimeter with in-situ tunable gain*, arXiv:2310.03489 [inst-det] (2023), doi:10.48550/arXiv.2310.03489.
personal contribution: contributing author, leading PI of activity, PhD supervisor.

Academic Distinctions

2015	Award for outstanding teaching, Heidelberg University, Germany
2013	Ruprecht-Karls-Prize for outstanding thesis, Heidelberg University, Germany

Other Information

since 2022	Member of the DELight Collaboration *DELight is a proposed experiment using superfluid He to search for light DM.*
since 2011	Member of the ECHo Collaboration *ECHo measures the neutrino mass from the ^{163}Ho electron capture spectrum.*

Data protection and consent to the processing of optional data

If you provide voluntary information (marked as optional) in this CV, your consent is required. Please confirm your consent by checking the box below.

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Curriculum Vitae: Prof. Dr. Belina von Krosigk

Personal Data

Title	Prof. Dr.
First name	Belina
Name	von Krosigk
Current position	Professor of Experimental Physics
Current institution(s)/site(s), country	Heidelberg University, Germany
Identifiers/ORCID	0000-0001-5223-3023

Qualifications and Career

Stages	**Periods and Details**	
Degree program	2010	Physics, University of Hamburg, Germany
Doctorate	2015	Prof. Dr. K. Zuber, *Measurement of proton and α–particle quenching in LAB based scintillators and determination of spectral sensitivities to supernova neutrinos in the SNO+ detector*, Technical University Dresden, Germany
Stages of academic/ professional career	since 2023	Full Professor (W3), Heidelberg University, Germany
	2019-2023	Emmy Noether Junior Research Group Leader, University of Hamburg / KIT, Germany
	2015-2019	post-doctoral researcher at University of British Columbia, Vancouver, Canada
	2015	post-doctoral researcher at Technical University Dresden, Germany

Supplementary Career Information

none

Activities in the Research System

since 2022	Appointed operations coordinator of the SuperCDMS DAQ and trigger system
since 2021	Co-organizer of the EXCESS Workshop series *Community-wide, collaborative effort to increase the understanding of sensitivity-limiting excess of background events.*
since 2020	Elected member of the SuperCDMS Executive Committee
since 2020	Appointed SuperCDMS Safe Person *Ombudsperson and Safe People help members to navigate difficult situations.*
since 2020	Mentor within the dynaMENT program *Mentoring program for female- and non-binary-identifying researchers in natural sciences, DESY and MIN faculty of University of Hamburg.*
2019 - 2021	Elected representative of the Young Investigator Network (YIN) at DESY/Universtity of Hamburg
2016 - 2022	Appointed project manager of the SuperCDMS DAQ Software project (DOE) *The DAQ Software project covers the development, testing, and commissioning of all front-ends that control DAQ hardware, data flow, and triggering.*
2018 - 2020	Elected analysis coordinator (physics coordinator) at SuperCDMS

Scientific Results

Category A

1. H. Meyer zu Theenhausen, B. von Krosigk and J. S. Wilson, *Neural-network-based level-1 trigger upgrade for the SuperCDMS experiment at SNOLAB*, J. Instrum. 18 (2023) P06012, doi:10.1088/1748-0221/18/06/P06012.
   personal contribution: project coordination.

2. J. Wilson et al., *The level-1 trigger for the SuperCDMS experiment at SNOLAB*, J. Instrum. 17 (2022) P07010, doi: 10.1088/1748-0221/17/07/P07010.
   personal contribution: project and local coordination, my group conducted all trigger performance tests and authored the respective paper sections.

3. Y. Hochberg, B. von Krosigk, E. Kuflik and T. C. Yu, *Impact of Dark Compton Scattering on Direct Dark Matter Absorption Searches*,
   Phys. Rev. Lett. 128 (2022) 191801, doi: 10.1103/PhysRevLett.128.191801.
   personal contribution: lead author, project coordination, limit calculation.

4. A. M. Deiana et al., *Applications and Techniques for Fast Machine Learning in Science*,
   Front. Big Data 5 (2022) 787421, doi:10.3389/fdata.2022.787421.
   personal contribution: author of the section for direct dark matter experiments.

5. B. von Krosigk et al., *Effect on Dark Matter Exclusion Limits from New Silicon Photoelectric Absorption Measurements*,
   Phys. Rev. D 104 (2021) 063002, doi: 10.1103/PhysRevD.104.063002.
   personal contribution: lead author, project coordination.

6. C. Stanford et al., *Photoelectric absorption cross section of silicon near the band gap from room temperature to sub-Kelvin temperature*,
   AIP Advances 11 (2021) 025120, doi: 10.1063/5.0038392.
   personal contribution: local coordination, my group provided the initial motivation for the measurements, was leading the analytic modeling of the data, and main author.

7. SuperCDMS Collaboration, *Constraints on dark photons and axion-like particles from SuperCDMS Soudan*,
   Phys. Rev. D 101 (2020) 052008; err. Phys. Rev. D 103 (2021) 039901,
   doi: 10.1103/PhysRevD.101.052008.
   personal contribution: sensitivity calculations, initiator and coordinator of the analyses.

8. SuperCDMS Collaboration, *Constraints on low-mass, relic dark matter candidates from a surface-operated SuperCDMS single-charge sensitive detector*,
   Phys. Rev. D 102 (2020) 091101, doi: 10.1103/PhysRevD.102.091101.
   personal contribution: local coordination, my group lead the analysis and the publication.

9. SuperCDMS Collaboration, *First Dark Matter Constraints from a SuperCDMS Single-Charge Sensitive Detector*,
   Phys. Rev. Lett. 121 (2018) 051301; err. Phys. Rev. Lett. 122 (2019) 069901, doi: 10.1103/PhysRevLett.121.051301.
   personal contribution: one of the lead analyzers and main authors.

10. B. von Krosigk et al., *Measurement of α-particle quenching in LAB based scintillator in independent small-scale experiments*,
    Eur. Phys. J. C 76 (2016) 109, doi: 10.1140/epjc/s10052-016-3959-2.
    personal contribution: lead author, project coordination.

Category B

1. F. Toschi et al., *Optimum filter-based analysis for the characterization of a high-resolution magnetic microcalorimeter towards the DELight experiment*, arXiv:2310.08512 [hep-ex] (2023), doi:10.48550/arXiv.2310.08512 *submitted to Phys. Rev. D for publication.*
   personal contribution: project coordination, contribution to data analysis and interpretation.

Academic Distinctions

2022	Hertha-Sponer-Prize 2023 of the German Physical Society DPG *Annually awarded to female physicists for outstanding research.*
2019	Emmy-Noether Junior Research Group grant (funds for 6 years)

Other Information

since 2022	Spokesperson of the DELight project *DELight is a proposed experiment using superfluid He to search for light DM.*
since 2020	Member of the DARWIN collaboration *DARWIN is a future liquid-xenon-based observatory for direct dark matter detection and other rare-event searches.*
since 2015	Member of the SuperCDMS collaboration *SuperCDMS is a direct dark matter search experiment using cryogenic semiconductor bolometers, currently built at SNOLAB, Canada.*
2013-2015	Member of the HALO collaboration *HALO is an experiment specialized for supernova neutrinos at SNOLAB.*
2010-2015	Member of the SNO+ collaboration SNO+ is dedicated to the search for neutrinoless double beta decay of ^{130}Te.
2008-2010	Member of the OPERA collaboration *OPERA was a high-energy neutrino beam detector at LNGS.*

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Curriculum Vitae: Dr. Sebastian Lindemann

Personal Data

Title	Dr.
First name	Sebastian
Name	Lindemann
Current position	Senior Researcher (Current contract ends December 31, 2024. Promotion to a permanent E14 scientist position is currently ongoing. The process will be completed at the anticipated start date of the RU.)
Current institution(s)/site(s), country	University of Freiburg, Germany
Identifiers/ORCID	0000-0002-4501-7231

Qualifications and Career

Stages	**Periods and Details**	
Degree program	2009	Physics, Heidelberg University, Germany
Doctorate	2013	Prof. Dr. W. Hampel, *Intrinsic ^{85}Kr and ^{222}Rn Backgrounds in the XENON Dark Matter Search*, Heidelberg University, Germany
Stages of academic/ professional career	since 2018	Senior Scientist, Institute of Physics, University of Freiburg, Germany
	2016-2018	Postdoctoral Fellow, Institute of Physics, University of Freiburg, Germany
	2013-2016	Postdoctoral Fellow, Max-Planck-Institut für Kernphysik, Heidelberg, Germany

Supplementary Career Information

none

Activities in the Research System

since 2023	Working group leader "Electrodes" for XENONnT
since 2023	Elected member of the faculty council, Faculty for Mathematics and Physics, University of Freiburg
since 2022	Working group leader "Detector" for DARWIN
since 2020	Reviewer for the European Physical Journal (EPJ)
2018 – 2020	Task group leader "TPC field cage" for XENONnT
since 2018	Member of the "Jugend Forscht" scientific jury

Scientific Results

Category A

1. XENON Collaboration, *Search for New Physics in Electronic Recoil Data from XENONnT*, Phys. Rev. Lett. **129**, 161805 (2022), doi: 10.1103/PhysRevLett.129.161805.
personal contribution: leading role in detector construction and commissioning, contributing author.

2. DARWIN Collaboration, *Sensitivity of the DARWIN observatory to the neutrinoless double beta decay of ^{136}Xe*, Eur. Phys. J. **C 80**, 808 (2020), doi: 10.48550/arXiv.2003.13407.
personal contribution: analysis coordinated within group, supervision and discussions.

3. XENON Collaboration, *Observation of two-neutrino double electron capture in ^{124}Xe with XENON1T*, Nature **568** (2019) 532, doi: 10.1038/s41586-019-1124-4.
personal contribution: contributions to background model and internal referee.

4. XENON Collaboration, *Dark Matter Search Results from a One Tonne$\times$Year Exposure of XENON1T*, Phys. Rev. Lett. **121** (2018) 111302, doi: 10.1103/PhysRevLett.121.111302.
personal contribution: analysis coordinated within group, discussions and internal referee.

5. XENON100 Collaboration, *Intrinsic backgrounds from Rn and Kr in the XENON100 experiment*, Eur. Phys. J. **C 78** (2018) 132, doi: 10.1140/epjc/s10052-018-5565-y.
personal contribution: main author and corresponding author.

6. S. Bruenner, S. Lindemann et al., *Radon depletion in xenon boil-off gas*, Eur. Phys. J. **C 77** (2017) 143, doi: 10.1140/epjc/s10052-017-4676-1.
personal contribution: main author and corresponding author.

7. DARWIN Collaboration, *DARWIN: towards the ultimate dark matter detector*, J. Cosmol. Astropart. Phys. **11** (2016) 017, doi: 10.1088/1475-7516/2016/11/017.
personal contribution: internal referee.

8. H. Simgen, S. Lindemann et al., *Detection of ^{133}Xe from the Fukushima nuclear power plant in the upper troposphere above Germany*, J. Env. Rad. **132** (2014) 94, doi: 10.1016/j.jenvrad.2014.02.002. *personal contribution: main author*.

9. S. Lindemann and H. Simgen, *Krypton assay in xenon at the ppq level using a gas chromatographic system and mass spectrometer*, Eur. Phys. J. **C 74** (2014) 2746, doi: 10.1140/epjc/s10052-014-2746-1. *personal contribution: main author and corresponding author.*

10. XENON100 Collaboration, *Dark Matter Results from 225 Live Days of XENON100 Data*, Phys. Rev. Lett. **109** (2012) 131801, doi: 10.1103/PhysRevLett.109.181301. *personal contribution: contributed to data analysis and background model, internal referee.*

Category B

1. XENON Collaboration, *Design and performance of the field cage for the XENONnT experiment*, arXiv:2309.11996 [physics.hep-ex] (2023), doi: 10.48550/arXiv.2309.11996, *submitted to Eur. Phys. J. C for publication.*
   personal contribution: leading author and corresponding author.

Other Information

since 2022	Member of the DELight collaboration *DELight is a proposed experiment using superfluid He to search for light DM.*
since 2017	Member of the DARWIN collaboration *DARWIN is a future liquid-xenon-based observatory for direct dark matter detection and other rare-event searches.*
since 2009	Member of the XENON collaboration *XENON is dedictated to direct searches for dark matter. The international collaboration currently operates the XENONnT detector at the LNGS in Italy.*
2008-2009	Member of the GERDA collaboration *The GERDA experiment searched for neutrinoless double-beta decay of ^{76}Ge.*

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Curriculum Vitae: Prof. Dr. Marc Schumann

Personal Data

Title	Prof. Dr.
First name	Marc
Name	Schumann
Current position	Professor of Experimental Astroparticle Physics
Current institution(s)/site(s), country	University of Freiburg, Germany
Identifiers/ORCID	0000-0002-5036-1256

Qualifications and Career

Stages	**Periods and Details**	
Degree program	2004	Diploma in Physics, Heidelberg University, Germany
Doctorate	2007	Prof. Dr. H. Abele, *Measurement of Neutrino and Proton Asymmetry in the Decay of polarized neutrons*, Heidelberg University, Germany
Stages of academic/ professional career	since 2016	Full Professor (W3) of Experimental Astroparticle Physics, University of Freiburg, Germany
	2013-2016	Assistant Professor (Tenure Track), Albert Einstein Center, University of Bern, Switzerland
	2009-2012	Senior scientist (Oberassistent), University of Zurich, Switzerland
	2007-2009	Post-doctoral researcher, Rice University, Houston, USA
	2007	Post-doctoral researcher, Heidelberg University, Germany

Supplementary Career Information

Offer of promotion to Associate Professor (tenured) at University of Bern, Switzerland (2016). Declined.

Activities in the Research System

selected activties:

since 2020	Shift Treasurer of the XENON Collaboration
since 2019	Member of the faculty council of the Faculty of Mathematics and Physics, University of Freiburg
since 2018	Co-Spokesperson of the DARWIN Collaboration
2021-2023	Managing director of the Institute of Physics, University of Freiburg
2021-2023	Vice-dean of the Faculty of Mathematics and Physics, University of Freiburg
2019-2023	Deputy Member of the Senate, University of Freiburg
2019-2023	Ombudsperson of the XENON Collaboration
2019-2021	APPEC Dark Matter Committee *Committee of 12 scientists from experiment and theory to provide a review of the experimental programme of direct detection searches of particle DM.*
2016 - 2019	Contact person for big data and data preservation issues of the German astroparticle physics community (KAT)
2013 - 2016	Member of the Steering Committee, LHEP, University of Bern
2010 - 2013	Analysis Coordinator of the XENON Experiment
since 2010	International Organization Committee of PATRAS Workshop Series *Annual workshop on Axions, WIMPs and WISPs, with typically 150 attendees.*

Scientific Results

Category A

1. DARWIN, LZ, XENON Collaborations et al., *A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics*, J. Phys. G 50 (2023) 013001, doi: 10.1088/1361-6471/ac841a. *personal contribution: contributed several sections and figures, internal referee.*

2. XENON Collaboration, *Search for New Physics in Electronic Recoil Data from XENONnT*, Phys. Rev. Lett. 129 (2022) 161805. doi: 10.1103/PhysRevLett.129.161805.
personal contribution: internal referee and contributing author.

3. CAST Collaboration, *Search for Dark Matter Axions with CAST-CAPP*, Nature Comm. 13, 6180 (2022), doi: 10.1038/s41467-022-33913-6.
personal contribution: internal referee and contributing author.

4. XENON Collaboration, *Observation of two-neutrino double electron capture in ^{124}Xe with XENON1T*, Nature 568 (2019) 532, doi: 10.1038/s41586-019-1124-4.
personal contribution: suggested the science channel to XENON, contributing author.

5. XENON Collaboration, *Dark Matter Search Results from a One Tonne$\times$Year Exposure of XENON1T*, Phys. Rev. Lett. 121 (2018) 111302, doi: 10.1103/PhysRevLett.121.111302.
personal contribution: analysis coordinated by own group, internal referee.

6. DARWIN Collaboration, *DARWIN: towards the ultimate dark matter detector*, JCAP 11 (2016) 017, doi: 10.1088/1475-7516/2016/11/017.
   personal contribution: main author and corresponding author.

7. M. von Sivers, M. Schumann et al., *The GeMSE Facility for Low-Background γ-Ray Spectrometry*, JINST 11 (2016) P12017, doi: 10.48550/arXiv.1606.03983.
   personal contribution: conceptualized the facility, co-author.

8. M. Schumann et al., *Dark matter sensitivity of multi-ton liquid xenon detectors*, JCAP 10 (2015) 016, doi: 10.1088/1475-7516/2015/10/016.
   personal contribution: designed and led the analysis, main and correspronding author.

9. XENON100 Collaboration, *Dark Matter Results from 225 Live Days of XENON100 Data*, Phys. Rev. Lett. 109 (2012) 131801, doi: 10.1103/PhysRevLett.109.181301.
   personal contribution: coordinated the analysis, main and corresponding author.

10. M. Schumann et al., *Measurement of the Neutrino Asymmetry Parameter B in Neutron Decay*, Phys. Rev. Lett. 99 (2007) 191803, doi: 10.1103/PhysRevLett.99.191803.
    personal contribution: planned and conducted experiment and analysis, corresponding author

Category B

1. D. Wiebe, S. Lindemann, M. Schumann, *A High-Sensitivity Radon Emanation Detector System for Future Low-Background Experiments*, arXiv:2309.04514, doi: 10.48550/arXiv.2309.04514.
   personal contribution: conceptualized the facility, co-author.

2. M. Androver et al. (DARWIN Collaboration), *Cosmogenic background simulations for the DARWIN observatory at different underground locations*, arXiv:2306.16340, doi: 10.48550/arXiv.2306.16340. *personal contribution: group involved in study, co-author.*

3. D. Masson et al., *Doberman: Slow Control and Monitoring*, distributed supervisory control, data acquisition, and monitoring software for small- to medium-size experiments, `https://github.com/AG-Schumann/Doberman`.
   personal contribution: conceptualized the system, supervises the project.

4. J. Billard, M. Schumann et al., *Direct Detection of Dark Matter – APPEC Committee Report*, Rep. Prog. Phys. 85, 056201 (2022), doi: 10.1088/1361-6633/ac5754.
   personal contribution: author of general introduction to WIMP searches and the liquid xenon sections.

5. DARWIN Collaboration, *The DARWIN astroparticle physics observatory*, Letter of Intent to the Gran Sasso Underground Laboratory of INFN (2019).
   personal contribution: main and corresponding author.

Academic Distinctions

2016	ERC Consolidator Grant ULTIMATE
2007-2009	G. K. Walters Fellowship, Rice University (US)

Other Information

since 2022	Member of the DELight collaboration
since 2020	Member of the SHiP collaboration *SHiP is a proposed proton beamdump experiment at CERN to search for hidden sector particles such as heavy neutral leptons.*
2017-2023	Member of the CAST collaboration *The CAST experiment at CERN searched for hypothetical solar axions.*
since 2010	Member of the DARWIN collaboration *DARWIN is a future liquid-xenon-based observatory for direct dark matter detection and other rare-event searches.*
since 2007	Member of the XENON collaboration *XENON is dedictated to direct searches for dark matter. The international collaboration currently operates the XENONnT detector at the LNGS in Italy.*
2002-2007	Member of the PERKEO collaboration *The PERKEO collaboration operated electron spectrometers to precisely measure parity violating parameters in neutron decay.*

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Curriculum Vitae: Prof. Dr. Kathrin Valerius

Personal Data

Title	Prof. Dr.
First name	Kathrin
Name	Valerius
Current position	Professor of Experimental Astroparticle Physics
Current institution(s)/site(s), country	Karlsruhe Institute of Technology, Germany
Identifiers/ORCID	0000-0001-7964-974X

Qualifications and Career

Stages	**Periods and Details**	
Degree program	1999-2004	Physics (diploma), Bonn University, Germany
Doctorate	2005-2009	Prof. Dr. Ch. Weinheimer, *Spectrometer-related background processes and their suppression in the KATRIN experiment*, University of Münster, Germany
Stages of academic/ professional career	since 2020	Full professor (W3), Karlsruhe Institute of Technology, Germany
	2014-2020	Helmholtz Young Investigator Group leader, Karlsruhe Institute of Technology, Germany
	2013-2014	Visiting researcher at Laboratoire Astro-particule et Cosmologie, Paris, France
	2009-2014	Post-doctoral researcher (Akad. Rat a. Z.) at Erlangen Centre for Astroparticle Physics, University Erlangen-Nürnberg, Germany

Supplementary Career Information

none

Activities in the Research System

selected activities:

since 2022	Deputy chair of the German Committee for Astroparticle Physics (KAT)
since 2022	Co-spokesperson of the KATRIN collaboration
since 2021	Commission for Early-Career Researchers (KWN), physics department, KIT
since 2022	Delegate of Equal Opportunities Officer of KIT to physics faculty council
since 2019	Deputy spokesperson of the Topic *Matter and Radiation from the Universe* in the Helmholtz Research Field *Matter*
2017-2020	Representative Speaker of the Young Investigator Network (YIN) at KIT
since 2017	Member of the Advisory Committee for the Erice School of Nuclear Physics
since 2017	Co-spokesperson (with L. Gastaldo) of the international network *Absolute neutrino mass scale from nuclear beta decay and electron capture*; co-organizer of the network's bi-annual "NuMass" workshop series
2015-2016	Topic representative *Dark Universe* in the Member Board of the Helmholtz Alliance for Astroparticle Physics (HAP)
since 2015	Course Committee member in the graduate school KSETA at KIT; since 2023 member of Admission Panel and Executive Board, Steering Committee member of the KIT Center Elementary Particle and Astroparticle Physics (KCETA)
2010-2014	Outreach coordinator for the Erlangen node of Netzwerk Teilchenwelt / International Particle Physics Masterclasses / QuarkNet / Cosmic-Ray e-Lab
since 2009	Mentor for early-career researchers in various programs
2009-2013	Steering Committee member, Physics Institute, University Erlangen-Nürnberg

Scientific Results

Category A

1. DARWIN, LZ, XENON Collaborations et al., *A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics*,
   J. Phys. G 50 (2023) 013001, doi: 10.1088/1361-6471/ac841a.
   personal contribution: group contributed to neutrino-physics program.

2. KATRIN Collaboration, *Direct neutrino-mass measurement with sub-electronvolt sensitivity*,
   Nature Physics 18 (2022) 160, doi: 10.1038/s41567-021-01463-1.
   personal contribution: leader of one of the analysis teams, editorial contributions.

3. KATRIN Collaboration, *New Constraint on the Local Relic Neutrino Background Overdensity with the First KATRIN Data Runs*,
   Phys. Rev. Lett. 129 (2022) 011806, doi: 10.1103/PhysRevLett.129.011806.
   personal contribution: contributing author, internal review.

4. XENON Collaboration, *Search for New Physics in Electronic Recoil Data from XENONnT*,
   Phys. Rev. Lett. 129 (2022) 161805, doi: 10.1103/PhysRevLett.129.161805.
   personal contribution: contributing author.

5. A. Lokhov, S. Mertens, D. S. Parno, M. Schlösser, and K. Valerius,
   Probing the neutrino-mass scale with the KATRIN experiment,

Ann. Rev. Nucl. Part. Sci. 72 (2022) 259, doi: 10.1146/annurev-nucl-101920-113013.
personal contribution: paper coordinator and corresponding author.

6. KATRIN Collaboration, *Improved eV-scale sterile-neutrino constraints from the second KATRIN measurement campaign*,
Phys. Rev. D 105 (2022) 072004, doi: 10.1103/PhysRevD.105.072004.
personal contribution: supervisor of one of the lead analysts and corresponding authors.

7. KATRIN Collaboration, *Analysis methods for the first KATRIN neutrino-mass measurement*,
Phys. Rev. D 104 (2021) 012005, doi: 10.1103/PhysRevD.104.012005.
personal contribution: paper co-organizer, writing and editorial contributions.

8. KATRIN Collaboration, *Improved Upper Limit on the Neutrino Mass from a Direct Kinematic Method by KATRIN*,
Phys. Rev. Lett. 123 (2019) 221802, doi: 10.1103/PhysRevLett.123.221802.
personal contribution: leader of one of the analysis teams, editorial contributions.

9. M. Kleesiek et al., *Beta-Decay Spectrum, Response Function and Statistical Model for Neutrino Mass Measurements with the KATRIN Experiment*,
Eur. Phys. J. C79 (2019) 204, doi: 10.1140/epjc/s10052-019-6686-7.
personal contribution: paper coordinator, analysis team leader.

10. H.E.S.S. Collaboration, *The population of TeV pulsar wind nebulae in the H.E.S.S. Galactic Plane Survey*, Astron. Astrophys. 612 (2018) A2, doi: 10.1051/0004-6361/201629377.
personal contribution: one of the main analysts and corresponding authors.

Category B

1. D. S. Parno and K. Valerius, *Probing the neutrino mass scale with the KATRIN experiment*,
Europhysics News 53(1), 2022, 24-27, doi: 10.1051/epn/2022107.
personal contribution: corresponding author.

2. M. Klein, P. Niemann, P. Schrögel, K. Valerius et al., *KATRIN Virtual Reality Tour*, released in July 2021, http://vr.nawik.de.
Created in cooperation with the National Institute for Science Communication.
personal contribution: project initiator, scientific supervisor, contributing author, presenter.

3. G. Drexlin, K. Valerius, Ch. Weinheimer, *Den kosmischen Leichtgewichten auf der Spur*,
Physik in unserer Zeit 51(3), 2020, 116-122, doi: 10.1002/piuz.202001576.
personal contribution: corresponding author.

Academic Distinctions

2018	Helmholtz program for first-time professorial appointments of excellent women scientists (W2/W3)
2013	Helmholtz Young Investigator Group program

Other Information

since 2022	Member of the DELight collaboration *DELight is a proposed experiment using superfluid He to search for light DM.*
since 2019	Member of the XENON collaboration *XENON is an experiment to directly search for dark matter. The international collaboration currently operates the XENONnT detector at the LNGS in Italy.*
since 2016	Member of the DARWIN collaboration *DARWIN is a future liquid-xenon-based observatory for direct dark matter detection and other rare-event searches.*
2009-2014	Member of the H.E.S.S. collaboration *H.E.S.S. is an array of Cherenkov telescopes located in Namibia to detect very-high-energy gamma rays.*
since 2004	Member of the KATRIN collaboration *KATRIN is the world-leading direct neutrino-mass experiment. It is located at KIT in Karlsruhe, Germany, and operated by an international collaboration.*

Data protection and consent to the processing of optional data

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