Proposal on R&D on quantum sensors: the DRD5/RDq proto-collaboration

(signatory list in section 13.2)

ABSTRACT

The detector R&D roadmap initiated by ECFA in 2020 highlighted the large number of particle physics opportunities that targeted and collaborative R&D in the field of quantum sensors and related technologies can enable. The involved communities and the roadmap's Task Force 5 (TF5) have established a list of the most promising areas for investment and defined the R&D that would be needed to bring these to the level at which experiments building on them can be envisaged. This proposal lays out the resulting high level work packages with deliverables and milestones and proposes the structure of a collaboration (the DRD5 / RDq collaboration) that would enable such R&D to be pursued at a global scale.

Keywords: quantum sensors, particle physics, BSM

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1. EXECUTIVE SUMMARY

The field of high energy physics has been driven to long-term international collaborative efforts on detector R&D by the numerous challenges posed by the very large and costly devices needed for the relevant experiments. Such a common endeavor that would go beyond numerous field-specific efforts in the hugely diverse, highly dynamic, and rapidly evolving field of quantum sensors, with the goal of advancing a wide range of technologies of great benefit to particle physics on a global scale, appears not to have been attempted yet.

Instead of addressing the needs of individual areas of particle physics, this proposal focuses on a set of Work Packages that the conveners and the communities that form part of their networks (the “signatories”) have identified as being potentially specifically and broadly relevant, and that would particularly benefit from *targeted* and *collaborative* R&D efforts on a *global* scale. Such a collaborative effort could lead to advances that individual efforts would not be expected to achieve, to the benefit of both the field of quantum technologies and the field of particle physics.

Finally, in addition to the set of Work Packages enumerated in this proposal, a possible collaborative structure and an organization of the distribution of the work that are matched to the specific needs of this global effort are presented.

2. INTRODUCTION

In the context of developing and preparing technologies for upcoming challenges of fundamental research, the European Committee for Future Accelerators (ECFA) initiated a process that culminated in 2021 with the publication of a detector R&D roadmap that laid out the challenges that future particle physics experiments will face [1]. This roadmap highlighted the importance of targeted detector R&D in a range of areas relevant to particle physics that need to be addressed, among them detectors in the realm of quantum sensing. Six families of quantum sensors were highlighted as particularly relevant to the study of nature at its most fundamental level. In 2022 all areas, represented by the conveners of the respective task forces of the roadmap, were encouraged to implement their respective R&D efforts in the form of dedicated collaborations and to prepare and submit appropriate proposals to a new scientific committee at CERN, the Detector R&D Committee (DRDC). This proposal presents a proposed path for the implementation of the R&D program for detectors for quantum and emerging technologies, described in Chapter 5 of the ECFA roadmap.

The structure of this proposal is the following: in the first part, an overview of the most promising areas linked to the ECFA roadmap is provided, a general overview in Chapter 4 and individual work packages in Chapters 5–9. Each high-level Work Package (WP) will be introduced with a short overview of the physics cases where relevant, and each sub-WP will be discussed in more detail, including a targeted timeline and milestones. An overview of the required and available resources is provided for each WP.

Building a workforce conversant in quantum techniques is discussed in Chapter 10. A summary of all the WP’s is given in Chapter 11. Collaborative, organizational, and intellectual property-related issues are addressed in Chapter 12. Finally, a list of the signatories is provided in Appendix 1; this list is only a snapshot at the moment of submission and can be expected to evolve in the course of time.

First, however, we wish to highlight an aspect that differentiates the implementation of the ECFA roadmap on quantum sensing from those of the other technology areas that form part of that roadmap. While for the latter, there are both pre-existing communities and consensus on which areas are most critically in need of R&D to match requirements for future high energy physics challenges, this is not the case for R&D on quantum sensors for particle physics. Neither are there existing communities that have previously collaborated on R&D at a large scale in the respective areas covered in this proposal, nor is there at the moment a solid consensus on which areas would be most critically in need of a dedicated effort. To address these two points, a workshop took place at CERN from April 3–6, 2023, including experts from all six areas covered in Chapter 5 of the ECFA roadmap, and incorporating proposals submitted by the wider communities in response to a call sent out about ten weeks prior to the workshop. The present proposal is based on a White Paper (retrievable on https://indico.cern.ch/event/1278425/) that represents the outcome of that workshop, the outcome of a second, "town-hall" workshop that took place at CERN on October 2–4, 2023, as well as continuous input from the corresponding communities. The current proposal must be considered an evolving document. The structure itself of the collaboration (outlined in Chapter 12) reflects this fluid process and ensures that it is able to evolve to address the expected changes in composition and focus of this global endeavor.

3. RATIONALE FOR A COLLABORATIVE R&D EFFORT

The field of high energy physics has been driven for decades to long-term international collaborative efforts on detector R&D given the numerous challenges posed by the very large and costly devices needed for the relevant experiments, but also because common standardized solutions that can be scaled up have been central to their conception and construction.

No such common driver has encouraged similar efforts in the hugely diverse, highly dynamic, and rapidly evolving field of quantum sensors. In spite of its track record in tackling technical challenges and in reducing entry costs through standardization in the field of high energy physics, such an approach may not necessarily be appropriate for the field of quantum sensors, with its often smaller and dynamic groups. However, also within that field, there are challenges where a collaborative effort could lead to advances that individual efforts would not be expected to achieve, from which both the field of quantum technologies and the field of particle physics can benefit.

We wish to emphasize here that both quantum technology and particle physics communities will need to be involved, both intellectually and financially, if such advances with mutual benefit are to be attempted. Formulating the challenges and the directions of attack coherently can provide funding agencies with a global view that will contextualize individual efforts, will help identify similar and complementary approaches on a global scale, and will provide an exchange point for the sharing of corresponding expertise, workforce, and educational frameworks.

Prior efforts at national scales have demonstrated that such an approach can result in tangible benefits, if the challenges of cross-disciplinary and cross-border collaborative endeavors are overcome. The aim of this roadmap implementation is thus to provide a framework within which similarly beneficial detector R&D can be carried out as part of a coordinated global effort within a few overarching sets of related activities (in the form of work packages). Given the global nature of this effort, it is natural that within each of these work packages, a range of complementary activities will take place. What the WP provides is a common framework in which resources, expertise, and goals can be shared and compared.

4. QUANTUM SENSING WORK PACKAGE OVERVIEWS

The ECFA process itself had identified quantum technologies as a promising path for particle physics and has identified, in particular, six families of quantum sensors (Table 1) as particularly relevant for particle physics. For each of these families, scientific motivations were presented during both a dedicated symposium in 2021 (https://indico.cern.ch/event/999818/) and in the roadmap itself.

clocks and clock networks	superconducting & spin-based sensors	kinetic detectors	atoms/ions/molecules & atom interferometry	optomechanical sensors	nano-engineered / low-dimensional

Table 1. Families of quantum sensors highlighted in the ECFA detector R&D roadmap

The approach taken in this proposal is complementary to that followed during the ECFA roadmap development. Rather than structure the discussions around physics domains and list the most salient challenges in those areas that the roadmap had identified as high-impact physics targets, or alternatively focus only on the quantum sensing families at a technical level, this document takes an intermediate approach. The following chapters propose a number of high-level Work Package-like lines of attack and highlight which areas among the six families of the ECFA roadmap are impacted by focused R&D on each of them, before focusing more narrowly on those aspects of the WPs that allow formulation in terms of specific goals, timelines, milestones and deliverables.

This structure thus mainly highlights the identified high-level and medium-level work packages, discusses the sub-families of technologies and systems that comprise them, and points out areas within them that would best be tackled by a collaborative global approach. In a number of cases, a brief reminder of the salient physics rationales for the specific quantum sensing families that comprise the different WPs will be given.

Sensor family → Work Package ↓	clocks & clock networks	superconducting & spin-based sensors	kinetic detectors	atoms / ions / molecules & atom interferometry	opto-mechanical sensors	nano-engineered / low-dimensional / materials
WP1 *Atomic, Nuclear and Molecular Systems in traps & beams*	X			X	(X)	
WP2 *Quantum Materials (0-, 1-, 2-D)*		(X)	(X)		X	X
WP3 *Quantum superconducting devices*		X				(X)
WP4 *Scaled-up massive ensembles* (spin-sensitive devices, hybrid devices, mechanical sensors)		X	(X)	X	(X)	X
WP5 *Quantum Techniques for Sensing*	X	X	X	X	X	
WP6 *Capacity expansion*	X	X	X	X	X	X

Table 2. High-level work packages (built on identified global challenges) and their overlap (indicated by "X") with the quantum sensor families of the ECFA detector R&D roadmap. Parentheses indicate a tentative or potential impact. These work packages can encompass both experimental and theoretical aspects.

5. WP-1 : ATOMIC, IONIC, NUCLEAR AND MOLECULAR SYSTEMS AND NANOPARTICLES IN TRAPS & BEAMS

This work package covers three large areas: exotic systems (such as Rydberg systems, radio-isotopes, Highly Charged Ions – HCIs –, nanoparticles, or antimatter systems), atom interferometry (with a focus on their potential for dark matter searches and their sensitivity to gravitational waves) and clocks (atomic, nuclear, ionic, molecular) and the challenges related to establishing networks of them. The three areas naturally result in sub-WP's (WP-1a, WP-1b and WP-1c), each with their own timelines and milestones.

5.1 WP-1a : Exotic systems in traps and beams

High sensitivity searches for physics beyond the standard model (BSM) or for violations of fundamental symmetries rely on probing a wide range of systems (trapped atoms, ions, molecules, nanoparticles, or beams thereof). While these systems have already led to highly sensitive searches for new physics through precision measurements of masses, transitions, or g-factors, it is not clear that these are the optimal systems for specific searches, and it is easy to conceive of many others that have to date not yet been experimentally realized, even in highly active fields (such as that of HCIs, of Rydberg systems, or of radio-isotopes).

Work Package	clocks & networks	super-conducting	kinetic sensors	atoms/ions/ molecules	opto-mechanical	nano-engineered / low-dimensional
WP-1a_a (exotic systems)	E			E	(E)	
WP-1a_b (bound state calculations)				T		
WP-1a_c (global analysis)	X	X	X	X	X	X

Table 3. Quantum sensor families impacted by R&D in WP-1a. E stands for an impact on experimental physics, T for one on theory. Parentheses indicate a tentative or potential impact.

5.1.1 Physics drivers

Atoms, molecules, and (possibly highly-charged) ions – including their antimatter or mixed-matter counterparts – in traps offer extraordinary sensitivity to dark matter-induced shifts or temporal variations of internal energy levels, allow tests of the equivalence principle, or allow searching for violations of fundamental symmetries (e.g. Lorentz- or CPT-invariance). Further areas of application are highly sensitive searches for variations of fundamental constants, tests of QED, or searches for non-SM interactions (fifth forces) [2], which can also be carried out via Ramsey spectroscopy of gravitationally bound quantum states of ultra-cold neutrons [3]. Diatomic molecules are the focus of several attempts to improve the limits on the electric dipole moment (EDM) of the electron using ThO, HfF+, RaF, with first exploration of the potential of poly-atomic molecules to improve sensitivity even beyond those systems [4]. These systems also provide a window into searches for hadronic T-violation or CP-violation in the nucleus (RaF, RaOH+). Similarly, searches for a neutron EDM via the Ramsey technique probe BSM CP-violating interactions at scales up to 1300 TeV [5], with the potential of a further order of magnitude in sensitivity. Larger trapped objects such as nanoparticles also offer prospects for high sensitivity to dark matter, both for particle-like [6, 7] and wave-like [8] dark matter. Levitated particles also offer prospects for detecting high frequency gravitational waves from beyond the standard model sources, such as axions [9, 10], for testing quantum foundations and how gravity can entangle massive superpositions [11–15], and for searching for exotic short-range corrections to Newtonian gravity [16, 17]. Similarly, matter-wave interferometers can test fundamental physics and physics beyond the Standard Model [18, 19], and can also test metric and curvature, as well as search for high frequency gravitational waves[20]. Nanoparticles are also well suited to search for exotic millicharged particles [21].

5.1.2 WP-1a_a: extension and improved manipulation of exotic systems

Exploration of novel production mechanisms (anti-protonic atoms as gateways to trapped, fully stripped nuclei, or to hydrogen-like Rydberg HCIs), of novel species (polyatomic, laser-coolable molecular systems) or extension of existing techniques to all potential systems (e.g. laser-cooling of negatively charged systems, either atomic or molecular) are all needed to enhance the set of available systems for experimental investigation. Which system is optimal for which particular goal is a question for theoretical studies (WP-1a_c), but vice-versa, being able to access a system at the highest sensitivity to a particular test of known physics or a specific BSM interaction requires establishing a range of techniques to prepare and manipulate a much wider range of systems than are currently accessible.

A particular category concerns molecules with radionuclides for EDM searches[22], with a reach in terms of SUSY sensitivity beyond 10 TeV masses. Although there is overlap with WP-4, this category will be treated here because these systems are mostly (but not exclusively) investigated in small numbers, What is needed for this category are improvements to existing experiments, new trapping technologies, advanced quantum control (including cooling techniques) of molecules, and offline access to species of interest (with production, harvesting, and handling on a one-day time scale). There are ongoing efforts at ISOLDE, TRIUMF, FRIB on developing a "Beam to beaker to beam" process. Here, efforts on portable Penning and/or Paul traps with extremely high vacuum are particularly relevant.

For nanoparticle sensing and matter-wave interferometry experiments, advances are needed in improved-efficiency loading mechanisms, development of high-purity low optical absorption materials and materials amenable to laser refrigeration, low-mechanical loss optical substrates and coatings, cryogenic-compatible vibration isolation technologies, and improved optical detection methods using squeezed light.

5.1.3 WP-1a_b: Bound state calculations

Observables in bound systems, such as transition energies and g-factors, can be measured with record precision. To utilize this precision for certain types of new physics searches, experiment and theory must be confronted, suggesting to choose simple systems with 2 or 3 constituents. This procedure is useful to determine fundamental constants [23], test bound-state QED calculations, and measure nuclear properties [24, 25]. When the number of equations exceeds that of free parameters, one can search for new physics at the precision frontier (see e.g. [26–29]). The physics reach is forever at the level of the larger uncertainty between experiment and theory.

At present, the output, i.e. value of fundamental constants and new physics reach, of several completed and ongoing studies is limited by our understanding of bound-state QED for hydrogen-like systems, necessitating an effort on this front. Specific examples include the muon mass [30], Rydberg constant [31], deuteron charge radius [32], and theoretical predictions of the muonium Lamb shift [33] and gross structure [34]. Together with ongoing experiments [30, 35], improved calculations would enable an independent determination of the muon $g-2$ [36], crucial in order to shed light on the recently confirmed deviation between experiment and theory [37]. Considering other simple systems, effort is needed to better exploit measurements of bound-electron g-factors [38–40], transitions in molecular ions [41, 42], and the energy levels of helium [43–45] and helium-like ions [46, 47]. Beyond these systems, bound-state calculations are also significant for matter-wave interferometry and phases measured there [48].

On top of more refined "pure" QED calculations, there is a growing need for a better understanding of the internal structure of nuclei [49], and how it affects observables in atomic physics [50, 51]. These are especially pronounced in compact systems such as exotic atoms (see e.g. [52, 53] and references therein), and in the interpretation of hyperfine structure measurements [54, 55].

5.1.4 WP-1a_c: Global analysis in the presence of new physics

Effort is needed in order to identify the most promising systems to search for or constrain new physics model-agnostically.

- A birds-eye view on the landscape of well-motivated new physics scenarios and their effects on different measurements, including astrophysics and high-energy.
- Identify regions of the parameter spaces which are not already excluded by two or more highly different experiments.
- Calculate the effect of different families of new physics scenarios (e.g. Yukawa potential) on bound state systems, including more challenging many-body atomic systems (e.g. isotope shifts in complicated systems [56]).
- A robust, broadband search for new physics must also allow for the consistent estimation of fundamental constants in the presence of new physics [57].

5.2 WP-1b : Atom Interferometry

The field of atom interferometry spans a wide spectrum of fundamental physics applications, encompassing gravitational wave detection, searches for ultra-light dark matter candidates and dark energy, as well as precise tests of the Standard Model (e.g., measuring the fine structure constant or the equivalent principle) and quantum mechanics. In light-pulse atom interferometry, laser pulses are used to coherently split, redirect, and recombine matter waves. Also magnetic gradient pulses can be used: such atom-interferometry has recently allowed realizing a complete Stern-Gerlach interferometer on a chip [58].

In a gradiometer configuration, two or even several identical atom interferometers are run simultaneously on opposite ends of a baseline, using the same laser sources. A comparison of the individual atom interferometer signals yields a differential measurement that enables the cancellation of noise common to both interferometers. This, in principle, enables superior common-mode rejection of noise, allowing for the possibility of, for example, gravitational wave detection using a single baseline. A passing gravitational wave would modulate the baseline length, while coupling to an ultralight dark matter field can cause a modulation in the energy levels. Both of these could be detected via shifts in the atom interference fringes. This quantum technology combines the prospects for both gravitational wave detection and dark matter searches into a single detector design, and both science signals are measured concurrently [59–61].

Five fully-funded atom interferometry prototype projects with the aim of fundamental physics exploitation are currently in progress: a 10 m fountain at Stanford [62], the Matter-wave Atomic Gradiometer Interferometric Sensor MAGIS-100 [58, 63] at FNAL in the US, the Matter-wave Interferometer Gravitation Antenna MIGA [64] in France, the Very Long Baseline Atom Interferometer VLBAI [65] in Germany, and the Atom Interferometer Observatory and Network AION-10 [66] at Oxford, with potentially 100 m sites available in the UK or at CERN. These projects aim to demonstrate the feasibility of large-scale Atom Interferometry, paving the way for terrestrial km-scale experiments.

Discussions are already underway for km-scale detectors, including the European Laboratory for Gravitation and Atom-interferometric Research (ELGAR) in Europe [67, 68], MAGIS-km at the Sanford Underground Research Facility (SURF) in the US [63], AION-km at the STFC Boulby facility in the UK [66], and advanced Zhaoshan Atom Interferometer Gravitation Antenna (ZAIGA) in China [69].

The aim is to make at least one kilometer-scale detector operational by approximately 2035. These experiments will systematically explore the deci-Hertz band of gravitational waves, investigate potential ultralight dark matter, and demonstrate essential technologies needed for space-based atom interferometry missions like the Atomic Experiment for Dark Matter and Gravity Exploration (AEDGE) [70].

To advance the field further and achieve the sensitivity required for comprehensive exploration of extensive ultralight dark matter regions and the detection of gravitational waves in the yet unexplored deci-Hertz range, two key challenges have been identified and are addressed in two Work Packages:

- WP-1b_a: Terrestrial Very-Long-Baseline Atom Interferometry (TVLBAI) Roadmap (see section 5.2.1)
- WP-1b_b: High Precision Atom Interferometry (see section 5.2.2)

It is important to note that these Work Packages, especially WP-1b_b, address issues and challenges that are common to metrology, spectroscopy, as well as instrumentation and measurement techniques for time or frequency with very high accuracy. These are closely related to the WPs defined in section 5.3 and encompass aspects of atom entanglement and squeezing discussed in section 9.

work package	clocks & networks	super-conducting	kinetic sensors	atoms/ions/ molecules	opto-mechanical	nano-engineered / low-dimensional
WP-1b_a (Terrestrial VLBAI)	X			X		
WP-1b_b (high precision AI)	X			X		

Table 4. Quantum sensor families impacted by R&D on atom interferometry (AI) in WP-1b

5.2.1 WP-1b_a: Terrestrial Very-Long-Baseline Atom Interferometry Roadmap

The main immediate goals of this WP will be to develop a roadmap for the design and technology choices for one or several km-scale atom interferometry detectors to be ready for operation in the mid-2030s, supported by the technology stakeholder community and the user communities interested in its science goals. This roadmap will outline technological milestones as well as refine interim and long-term scientific goals.

To accomplish this goal, it will be necessary to form an international collaboration of all stakeholders, taking charge of the development of the technology and science roadmap. A first step in this direction was taken at the Terrestrial Very-Long-Baseline Atom Interferometry (TVLBAI) Workshop [60, 71] hosted at CERN in March 2023.

As a next step, there are plans to establish a TVLBAI proto-collaboration during a dedicated event in spring 2024. This proto-collaboration will be tasked with advancing the community-building process, defining the necessary instrumentation studies, and providing input for the design and site selection of one or more kilometer-scale detectors, which will serve as the foundation for the complete roadmap. The design studies for these new detectors will need to include the analysis of phase signatures from, and corresponding sensitivities to, new physics [72].

The main milestones are:

- Formation of proto-collaboration in year 1
- Instrumentation studies for the roadmap in year 2 to year 4
- TVLBAI roadmap outlining technological milestones as well as interim and long-term scientific goals in year 5.

5.2.2 WP-1b_b: High-Precision Atom Interferometry

While the main technology and science roadmap is under development, the first TVLBAI workshop at CERN [60, 71] has already identified one important R&D project, which is the accelerated development of High-Precision Atom Interferometry for both Rubidium and Strontium. For large-scale atom interferometry detectors to reach the necessary sensitivity for a comprehensive exploration of fundamental physics, especially gravitational waves, improvements to detector sensitivity are required. Four key challenge areas offer opportunities to gain several orders of magnitude in performance.

Increasing the source flux of ultracold atoms to $\geq 10^{12}$ atoms/s at $\leq 2\,\mu$K will have a direct impact on measurement precision. Techniques also need to be developed to efficiently generate, cool, trap, and collimate the atoms [68]. Work on large momentum transfer (LMT) and atom optics will enable extended interrogation sequences with high sensitivity. The development of continuous atom sources combined with high-repetition-rate launch and interleaved interferometry sequences will permit the simultaneous operation of multiple interferometers within the same instrument. Finally, the deployment of entangled atoms to create squeezed states that circumvent atom shot-noise offers a route to extreme precision. These technological challenges are common to the currently ongoing prototype projects, and this WP will provide a focal point to exploit synergies and foster the development of these efforts.

Notably, the High-Precision Atom Interferometry techniques proposed here will directly improve the physics potential of WP-1c, due to a strong synergy with high-precision atomic clocks. Specifically, by reducing shot noise and Dick noise, several of the following milestones could enhance the sensitivity of atomic clocks by 2-3 orders of magnitude. Therefore, it will be important to coordinate and exploit synergies with the work defined in section 5.3.

- High flux of cold atoms (Year 3)
    (a) Target a continuous flux of atoms $> 1 \times 10^{12}$ atoms/s at $< 2\,\mu$K

- WP-1b_b:M2: LMT and atom optics (Year 3)
  - (a) LMT with number of pulses $N > 1000$
  - (b) Extended interrogation times using novel LMT sequences and atom optics
- High-shot-rate, quasi-continuous atom interferometry (Year 5)
  - (a) high-repetition-rate launch of cold atoms
  - (b) selective addressing of in-flight atom clouds with simultaneous LMT sequences and readout
- Squeezed AI (Year 5)
  - (a) Demonstrate $> 20\,\mathrm{dB}$ squeezing, including $> 10\,\mathrm{dB}$ metrological gain
  - (b) Demonstrate squeezing techniques compatible with high-flux, high-shot-rate atom interferometry

5.3 WP-1c: Networks, Signal and Clock distribution

Atomic clocks have a long history in metrology, and offer the possibility of creating exquisitely precise timing and frequency references. This extraordinary sensitivity can be used as the basis for innovative fundamental physics experiments, for example, in searches for ultra-light dark matter. Recent advances, such as the use of optical frequencies for atomic clocks, have led to improvements of several orders of magnitude in precision [73]. Fundamental physics experiments typically rely on the comparison of two clocks with differing sensitivities and, thus, the importance of connecting or distributing the clocks or clock signals.

Numerous individual and locally-linked high precision "clocks" exist world-wide [74], and rely on a wide range of quantum techniques. The devices achieve sensitivity by being linked either locally or nationally, to allow frequency comparisons. Several approaches can be pursued to achieve the next level of sensitivity. Individual nodes can be transformed into a globally linked single detector, or heterogeneous devices can be connected into a single multi-modal device, allowing to constrain different putative BSM models that affect individual nodes differently. Alternatively, a global reference signal can be provided against which local nodes can be calibrated or compared. This work package combines collaborative efforts along two main research lines:

- WP-1c_a: Large-scale networked atomic clocks and global sub-ns time stamping
- WP-1c_b: Portable references and sources

work package	clocks & networks	super-conducting	kinetic sensors	atoms/ions/ molecules	opto-mechanical	nano-engineered / low-dimensional
WP-1c_a (clock network)	X					
WP-1c_b (portable clocks)	X					

Table 5. Quantum sensor families impacted by R&D in WP-1c

5.3.1 Physics drivers

Clock-based experiments can be used as a detector to search for a wide variety of new physics or interactions with unprecedented precision [2]. Since atomic clock frequencies rely on fundamental quantities such as the fine structure constant (α) or the proton-electron mass ratio (μ), the apparent variation of these constants can be an indicator of new physics from, for example, ultra-light dark matter. More exotic possibilities include quintessence-like models of dark energy, generic hidden-sector scalar fields, or more new physics from Kaluza-Klein, dilaton, or soliton models [75]. Clock-based experiments have shown promise in searching for violations of Lorentz invariance, local position invariance, and as tests of quantum gravity [76]. Networked high-precision clocks can search for transient phenomena due to cosmic strings or domain walls, and can search for macroscopic dark objects, such as topological defects and dark stars. Already, individual atomic and molecular clocks exhibit a high sensitivity to BSM effects and variations of fundamental constants, and many groups are already engaged in improving the precision of these systems [77, 78].

Building a global network of high-stability and high-accuracy clocks is beyond the capability of an individual research group. It requires tackling challenges in a collaborative fashion at a large scale. Such a network is essential for advancing international time and frequency standards and would allow applications such as relativistic geodesy and unprecedented sensitivity in the search for new physics. Secondly, sending standardized optical clocks to off-network sites on earth or in space could allow more stringent tests of relativity and could enable the detection of low-frequency gravitational waves. Lastly, optical clocks based on entangled states of atoms would lead to measurements with even higher stability, ultimately approaching the Heisenberg limit.It should also be pointed out that such a very large-scale clock network would greatly benefit other fields, such as Very Long Baseline Interferometry (VLBI) astronomy using radiotelescopes, or can help pave the way towards VLBI optical astronomy.

5.3.2 WP-1c_a: Large-scale clock network

Existing clock experiments serve as a proof of principle for a wide variety of new physics searches, but to achieve the best sensitivity, a networked approach offers many advantages [79–81]. Worldwide efforts towards developing ultra-precise clocks based on a wide variety of systems (different atomic elements, ions, molecules, or even nuclei) are pushing the precision of clocks to below 1 part in 10^{20} [77]. At the same time, these different systems have a wide range of different systematics and couplings to putative BSM physics. A dedicated optical frequency and time signal distribution network, one that would allow spreading of the local clock signals across a multi-nation, continental, or international network, would greatly benefit the community and would open up significant new parameter space.

High precision temporal comparison of signals from a wide range of quantum sensors at geographically separated positions has multiple benefits. On one hand, it can allow differentiating local glitches from valid signals, while reducing systematics. On the other hand, a distributed set of observations can allow identifying the temporal evolution and direction of a potential source behind these common observations. Networks offer the possibility to improve the limit from a single pair of clocks by a factor $\sqrt{N}$ for N pairs of clocks. Finally, high-resolution time stamping (O(10 ps)) on a global scale will result in a highly sensitive earth-sized detector able to integrate a wide range of quantum sensors.

A roadmap of the technical requirements and science case for a European-wide fibre network for research can be found in the CLOck NETwork Services (CLONETS) Design Study [82], and the study is continuing with the efforts of the GÈANT Core Time Frequency Network (C-TFN) [83]. This work provides an excellent starting point and a community with which to develop solutions compatible with clock-based fundamental physics searches. National efforts for stabilised fibre connections for fundamental physics, metrology and quantum communication are being developed in the USA and many other places around the globe. As a case study, QSNET is realising in the UK a network of clocks that features enhanced sensitivity to variations of fundamental constants [72]. The network includes clocks with different technology readiness levels: from established atomic clocks to highly charged ion clocks and molecular clocks. As shown in Fig. 1, there has been progress on an international network in Europe, but significant work remains.

In addition to optical fibre links, free-space time and frequency transfer is being steadily improved, and will be an important component to many fundamental physics experiments in the future. Quantum-limited frequency transfer has been demonstrated over distances of 300 km, and new terrestrial and space-based tests of fundamental physics are being proposed [84, 85].

The two aspects of research with clocks, i.e. high precision time-stamping to O(10 ps) and distribution of a highly precise continuous clock signal to provide a reference, are closely linked. The interest in time distributions and frequency dissemination over quantum networks has recently increased for both telecommunications applications (fast 5G networks) and scientific applications (ranging from gravitational wave detection to dark matter searches). Some of these new protocols require sub-nanosecond synchronisation, such as is offered by the CERN White Rabbit technology, currently allowing synchronization at the ns level. It is noteworthy that the

European Commission has chosen White Rabbit as a candidate technology for a future EU-wide optical fibre time dissemination network through their Alternative Position, Navigation, and Timing (Alt PNT) program [86].

Figure 1. Existing and future trans-European optical clock network

5.3.3 WP-1c_b: Portable references and sources

While direct distribution of optical frequencies via a trans-national optical clock network is feasible within a geographic region such as Europe, this is much more challenging on a global scale. To tackle the problem of comparing clocks at geographically widely separated stations, an alternative to optical distribution of a reference frequency is to clone a well-established reference, and geographically distribute identical systems. This requires the design and fabrication of standardized portable references, bearing in mind that both neutrals and charged species can play the role of reference clock systems.

Similar distribution needs are also apparent in the case of a generalization of beam-to-trap-to-beam sample ion approaches (WP-1a). Investigations relying on ions of radio-isotopes produced at facilities are currently limited to experiments carried out at the production facilities themselves, which are not necessarily the environments best suited to precision measurements. Portable devices for charged ions would allow transporting moderately long-lived species to a wide range of high-precision measurement devices.

Optical clocks based on neutral atoms in optical lattices and single ions in RF Paul traps are well-established as frequency standards [73]. Laboratory systems based on both technologies have demonstrated accuracy and stability near the design goals set out in this document, but this level of performance has not yet been demonstrated in a transportable package. Several efforts are currently underway around the world to design compact, robust optical clock systems that can be used for metrological applications, such as comparisons of frequency standards across intercontinental distances [87, 88].

Because the proposed tests of fundamental physics based on atomic clocks are demanding in terms of clock stability and clock accuracy, the design goals set out here for portable clocks meet or exceed the most ambitious proposals existing for international metrology. There is a need to first identify promising atomic species and system architectures that can meet the competing goals of very high performance, transportability, and cost. The choice of atomic species impacts the type of trap, the set of laser systems, and the level of control of environmental conditions that are necessary for operating the clock and meeting the performance requirements. Careful engineering of these systems to withstand and quickly recover from environmental shocks experienced during transport will be critical. A standardized approach relying on miniaturization and established readily available components would be greatly beneficial.

5.3.4 Time and frequency distribution via space

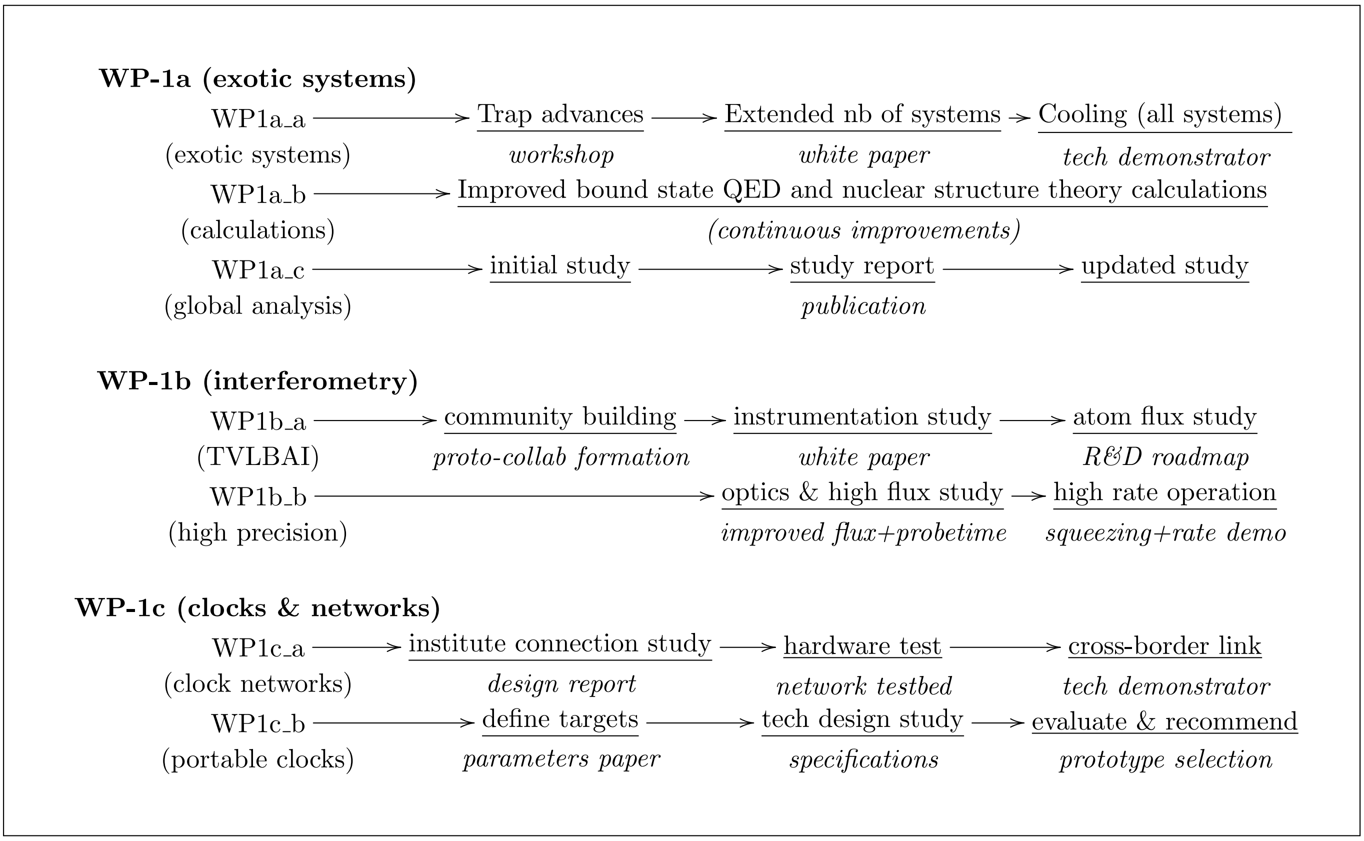
Another approach for comparing clocks at geographically separated stations not linked by optical fiber, is to do so from space, and approach that combines the challenges of WP-1c$_a$ and WP-1c$_b$. The advantage of this method is that it can reach any reasonable location on Earth, and possibly in real-time, depending on the implementation. Here, the time and frequency information from a ground station, typically a national metrology institute hosting ultra-precise and ultra-stable clocks, is sent to a transponder on a satellite and from there to any user elsewhere on the Earth surface. This time/frequency distribution requires sophisticated technology, in particular two-way transfer. Different approaches exist (pulsed optical, microwave), and they are at different levels of technology readiness. The hardware for the each ground user could eventually become of affordable cost.

ESA will launch the mission "ACES" to the ISS in 2025 to demonstrate the first-generation technology, enabling comparisons of clocks at the sub-1E-16 level. These clocks can be located at moderate distances or on different continents. A study on a next-generation transponder mission has been undertaken by ESA, promising 1E-18 level comparisons. The implementation of a next-generation mission requires the support of the community.

5.4 Milestones and deliverables WP-1 (years 1 / 3 / 5)

This WP seeks to build and develop a collaborative effort to pursue fundamental physics searches using quantum sensors as "clocks". Two approaches are followed; a networked approach where the clocks are connected via glass fibre, and by the development of high-specification, robust, reliable and transportable reference clocks. The goal is to move beyond the current single point-to-point connections, which mainly rely on local or national initiatives. There is a strong case for cross-national collaborative efforts to improve the sensitivity of fundamental physics searches, and extract a higher value out of the individual existing efforts. Addressing technical issues of implementation will constitute part of the milestones of this WP. On the other hand, for situations where geographic distances between nodes are great and cover thinly populated areas, a direct alternative to fiber optical distribution of a reference frequency must involve transportable references, as a precursor to eventual satellite-based systems.

Milestones are underlined, deliverables are in *italic.*



Example 1: Reducing shot noise and Dick noise, as proposed in WP-1b (a very high flux of ultracold atoms; high-shot-rate, quasi-continuous atom interferometry with squeezing), could enhance the sensitivity of atomic clocks by 2-3 orders of magnitude.

Example 2: Increasing the flux of cold atoms in atom interferometers enables sensitive searches for ultra-light dark matter.

Example 3: Formation of novel systems, such as hydrogen-like Rydberg Highly Charged Ions, enables fine-tuning - through choice of appropriate fully stripped radio-nuclei - of sensitivity to searches for BSM physics via precision spectroscopy of either excited states or of ground-state hyperfine splitting. Matter wave interferometry with nanoparticles enables tests of quantum mechanics and the role of gravity in quantum entanglement.

6. WP-2 : QUANTUM MATERIALS (0-, 1- AND 2-D MATERIALS)

Engineering materials at the atomic scale provides for a very wide range of behaviors that can be tuned to specific applications and forms the backbone of highly active fields worldwide. Specifically, applications in the area of particle physics can benefit from such custom materials based on quantum materials if the challenge of scaling up to macroscopic dimensions can be met (WP-4). Furthermore, novel solutions to a number of design challenges might become available to detector designers if their needs and the capabilities of quantum material designers could be matched (WP-6).

Low-dimensional materials very often exhibit properties that differ significantly from their bulk analogues due to quantum phenomena and can thus be considered the building blocks of “quantum materials” [89–97]. They are also often used as converters: wavelength shifters, ionizing particle to optical photons, photons to electrons, for example. Through incorporation into sensors, these materials, therefore offer great potential for future detection technologies. WP-2 focuses on exploring the role these components can play as elements of more complex dedicated assemblies such as those in WP-4.

6.1 WP-2a: Application-specific tailoring

To ensure that these atomic scale engineering advances benefit particle physics goals, it becomes important to identify a range of boundary conditions and optimization requirements which will allow selecting or developing appropriate materials. While the former is relatively straightforward, the latter constitutes targeted R&D towards materials that are optimally matched to existing and future device requirements. Such R&D thus encompasses e.g. developing nanodots and nanoplatelets whose emission properties are matched to the quantum efficiency of photodetectors, optimizing the luminescence properties of nanodots and nanoplatelets (for example, light yield or decay time), developing multi-layered semiconductor-based devices with phonon excitations or photon emission with LGAD-like temporal properties, optimizing the fabrication and layout of linear detection elements in lieu of planar arrays, the acceleration of the temporal response and the tunability of the emission by varying only the size of the object, etc.

A particular focus in the case of low-dimensional materials as components of devices in high energy physics is their radiation hardness. Whatever the intended application, one of the prerequisites for the use of nanomaterial scintillators (quantum dots, nanocrystals, nanoplatelets, ...) in calorimetry for high energy physics is, first, to be able to estimate their behavior as a function of irradiation. Tailoring and determination of radiation hardness will need to be investigated hand-in-hand.

In order to evaluate the performances of devices produced by a large number of active groups for a broad spectrum of applications, a standardized comparison procedure is desirable. As exemplified in the case of the performance of scintillators, a common protocol (x-ray induced decays and emission, relative scintillation yield, transmission) would allow evaluating performance against radiation and would enable setting up and maintaining an open database of these performance parameters, similar to that set up 30 years ago at Lawrence Berkeley National Lab (https://scintillator.lbl.gov/inorganic-scintillator-library/). Establishing such evaluation, fabrication, and validation protocols is a necessary first step while populating the corresponding databases would need to be implemented after each measurement campaign.

To exemplify and clarify the aims and strategy of this WP, we give here an example of the specific area of work related to 0-D (nanodots) and 2D (nanoplatelets) materials. WP-2a aims inter alia to survey the existing and potential “quantum scintillators”, to compare their properties following a standardized protocol, including radiation hardness, and to investigate their potential for use in future detectors as building blocks for more complex dedicated assemblies such as those in WP-4. Building a community and organizing the R&D on the use of quantum scintillating materials toward sensing for HEP is an underlying target.

Within the 0-D/2-D activities related to quantum-dot enhanced scintillators, for example, a number of milestones can be defined. A first milestone is the standardization of evaluation procedures, followed by a standardization of the evaluation of radiation hardness, while building the community. For each milestone, further milestones and deliverables must be envisaged.

6.2 WP-2b: Extended functionalities

Larger engineered structures (of the O(1∼10 μm) scale) have properties that are defined not only by their composition, but also by their geometries, internal layout, or applied fields. It is, in fact, quite complicated to dissociate *nm*-sized active objects (e.g., the nanoparticles) from their host environment. Such structures already allow building metalenses, for example, with tunable optical properties, devices with engineered emission and/or absorption bands in the optical, microwave, or THz range, and in general, dynamically reconfigurable properties. Contrary to existing structures, for which particle detector geometries have to some extent been optimized, such novel materials may enable reconsidering earlier optimization processes, may enable novel functionalities or may extend existing functionalities.

The communities involved in the design of particle detectors and those involved in nano-engineering are generally distinct; mutual awareness of the possibilities and the needs can trigger the development of novel approaches. With the example of nanocomposite scintillators, but more generally of nanocomposite structures in mind, the development of such nanocomposite materials involves promotion within the HEP community through workshops that bring together both nanomaterial and HEP communities with the goal of triggering the emergence of new detector concepts. An awareness of both what the design landscape can enable and what the specific requirements for particle detection and identification are, is the first necessary step upon which subsequent specific designs can be built.

6.3 WP-2c: Simulations

Given the close interaction between the individual quantum building blocks and their environment in terms of physics processes, they should not be considered as isolated objects but instead form a whole with their surrounding medium, the host. With this medium being discontinuous at small scales, an effective medium description is thus not suitable. First initiatives [98] at providing simulation packages to describe all relevant physics processes across multiple scales point the way. The aim here is to assess the feasibility of implementing a toolkit, initially dedicated to scintillators in general and nanoscintillators in particular, which includes solid-state physics aspects, incorporates processes at the molecular scale, and strives to reproduce the relevant processes through all stages of particle interactions with devices.

Such a new toolkit is envisioned to complement the existing models and simulations in libraries like Geant4 [99] which are extensively used in high-energy physics for modeling the passage of particles through matter. While Geant4 offers a comprehensive collection of successful models for a broad range of materials and interaction types, the proposed toolkit would enhance these capabilities by providing more detailed simulations at the nanoscale, particularly for novel quantum materials. This integration would bridge the gap between macroscopic material models and the intricate behaviours of materials at the quantum level, thereby enriching our understanding and predictive capabilities for particle interactions in complex detector environments.

A number of steps are required to reach the long-term goals which constitute natural WP milestones:

- Integration Development: Develop a Geant4 extension module to simulate quantum dot behaviours and scintillator responses upon interaction with charged particles. This module will also capture interface dynamics with host materials (see WP-4), ensuring seamless integration and system compatibility.
- Model Validation: Conduct a series of tests comparing simulation results with experimental data specifically for quantum dot-scintillator interactions, focusing on accuracy and reliability.
- Optimization: Optimize the simulation parameters and algorithms for computational efficiency and enhanced simulation fidelity, particularly for scenarios unique to quantum dot, scintillating and host materials.

The deliverables are:

- Extended Geant4 Module: A fully functional Geant4 module capable of simulating particle interactions with quantum dots in scintillating materials, complete with documentation and user guides.
- Validation and Performance Report: A concise report summarizing the validation results, performance benchmarks, and recommended applications of the extended module in particle physics research.

Work Package	clocks & networks	super-conducting	kinetic sensors	atoms/ions/ molecules	opto-mechanical	nano-engineered / low-dimensional
WP-2a (tailored materials)		(X)	(X)		(X)	X
WP-2b (extended functionalities)		(X)	(X)		(X)	X
WP-2c (simulations)		(X)	(X)		(X)	X

Table 6. Quantum sensor families impacted by R&D in WP-2

6.4 Milestones and deliverables WP-2 (years 1 / 3 / 5)

Milestones are underlined, deliverables are in *italic.*

WP-2 (0-,1- and 2-D materials)

WP-2a → characterization protocol → database definition → populated db
(application-specific tailoring) *protocol* *database prototype* *functional db*
WP-2ab → workshop/conference → device designs → novel hybrid devices
(extended functionalities) *device concepts* *prototype devices* *functional devices*
WP-2c → status & desiderata → prototype model → benchmarked simulations
(simulations) *report* *simulation SW designs* *validation report*

Example 1: Development of very bright and fast - O(10 ps) - nanocomposite scintillators, exceeding light yield and risetime of currently the brightest and fastest media, such as those based on self-assembled InAs quantum dots (QDs) embedded into a GaAs matrix [100].

Example 2: The Bluesky AidaInnova's project "NanoCal" [101] is developing advanced fine-sampling shashlik calorimeters using novel Nano-Composite (NC) scintillating materials. These materials involve perovskite or chalcogenide nanocrystals dispersed in a plastic matrix to create NC scintillators. This innovation aims to provide a cost-effective, performance-tailored alternative to traditional inorganic crystal scintillators for future large-volume detectors.

Usage of cesium lead bromide ($CsPbBr_3$) perovskite QDs as efficient wavelength shifters in photon detection systems in DUNE (Deep Underground Neutrino Experiment)[102]. These QDs effectively convert the vacuum ultraviolet scintillation light from DUNE's LAr detectors to wavelengths more suitable for detection by silicon photomultipliers (SiPMs), thus significantly improving detection efficiency. Notably, the $CsPbBr_3$ QDs have been shown to enhance photoluminescence quantum yields and present an economically viable option for large-scale production.

Example 3: Work on improved formulation, characterisation and radiation resistance of nanomaterial scintillators can result in novel functionality for existing HEP devices, such as the possibility of determining shower shapes within future "chromatic calorimeters". Such calorimeters would consist of different wavelength emitters along the axis of the scintillator, resulting in a chromatic differentiation of the locally deposited energy.

7. WP-3: CRYOGENIC MATERIALS, DEVICES AND SYSTEMS

Superconducting materials have been used extensively for the development of detectors with exquisite sensitivity. Indeed quantum-noise limited amplifiers and mixers, ultra-low-noise power detectors, and photon counting detectors are fabricated routinely and used in many scientific experiments. Much of this development has been carried out in the context of ground-based and space-based astronomical instruments, but the technology is starting to find its way into particle physics and fundamental physics more generally, with massive opportunities. In fact, large areas of astrophysics and numerous major international observatories would simply not exist if it were not for the development of superconducting sensors over the 3 mm to 30 μm (millimetre to far-infrared) wavelength range. Some of the most important ones are the Transition edge sensors (TES), Kinetic Inductance Detector (KID), Superconductor-Insulator-Superconductor (SIS) mixer, Hot Electron and Cold Electron Bolometer (HEB and CEB), Superconducting Nanowire Single Photon Detector (SNSPD), Superconducting Parametric Amplifiers (SPA), Superconducting Quantum Interference Device (SQUID) and the Magnetic Microcalorimeter (MMC). Crucially, however, the opportunities for superconducting microcircuit engineering are enormous. Multilayer and large-scale thin-film device processing based on the traditional low-Tc materials Nb, Al, Ta, Ti, Mo, Ir, Hf and the nitrided materials NbN, NbTiN, TiN etc., combined with the oxide films SiO_2, SiO and crystalline Si open the door to numerous device types, with considerable opportunities for innovating new device types, and large scale integrated components. Already, at millimetre and submillimetre wavelengths it is commonplace to integrate passive superconducting RF components, such as directional couplers, filters, hybrids and planar antennas, with arrays of superconducting amplifiers and detectors to build up RF microcircuits having high degrees of functionality.

It is important to appreciate that very few of the most important device types operate on the basis of idealised BCS theory. The majority of the superconducting materials are disordered and contain impurities and imperfections, and it is often second-order effects that drive the primary operating principles of the device, and certainly the second-order properties such as noise spectra. Thus, when engineering and combining different materials, it is essential to understand the precise details of the films being produced and their interfaces and to have secure theoretical models based, say, on Usadel's principles of disordered films. Every device producer knows that a large amount of work must go into creating devices that are free of artefacts, that can be manufactured in the form of arrays with high uniformity, and that are reproducible and indeed stable over long periods of time. One important area involves laying down several layers, typically two or three, of different materials, TiAu, MoCu, MoAu, to create new superconductors having bulk properties that are intermediate between those of the constituent films: for example, controlling T_c, conductivity, quasiparticle relaxation time, etc. These principles are used to produce low-T_c devices (<100 mK), and devices suitable for long wavelengths (< 3 mm).

An important consideration is that the characteristics of devices have to be designed and engineered to meet the needs of specific applications. The technology is applications driven because otherwise, the range of opportunities is simply too large to be explored without having a strong sense of direction. In addition, although sensitivity is often highlighted in scientific publications, other considerations such as linearity, bandwidth, speed, dynamic range, stability, and cooling requirements must be met simultaneously if a given device type is to be of any practical value. Despite these challenges, superconducting sensing technology is essential for observational astronomy and cosmology for existing and next-generation telescopes in the mm to FIR wavelength range, but also for NIR, UV and for x-ray astronomy and even gamma-ray spectroscopy. The application of these devices to searches for ultra-light dark matter, measuring the absolute mass scale of the neutrino, direct spectroscopy of massive particles such as electrons, and optical interferometric measurements of the quantum nature of spacetime are also now developing rapidly. In some cases, only single devices are needed, whereas in other cases, large kilo-pixel arrays are the ambition. This brings the new challenge of multiplexing, which is usually, but not necessarily, also done using superconducting electronics. TESs, KIDs, SNSPDs, SPAs are all being developed to tackle the need for large arrays. As an example of the importance of high-quality engineering at high technological readiness level (TRL), many of the next space-based astronomy telescopes are completely reliant on the development of a new generation of complex superconducting focal-plane technology.

Many of the most important elemental superconductors are refractory metals having high melting points (2,500 K for Nb, 1,700 K for Ti), and so high temperature sputtering is needed to enable the production of thin films (50 - 200 nm). Once produced, however, they are durable and grow hard oxides, forming a natural passivation, but this also affects device behaviour at the microscopic level. In addition, ultra high vacuum (UHV), 10^{-10} mbar, deposition systems are essential for growing superconducting films with sufficiently low impurity levels. Other techniques such as controlling the temperature of the substrate during deposition from 77 K to 900 K to determine the stoichiometry and morphology, and rotating the substrate to achieve uniformity, are also used. In the case of nitrided superconductors, reactive UHV sputtering is used, allowing a wide range of material characteristics to be achieved. Also, when subsequent films are laid down and patterned, the techniques become more involved. The key point is that this is an advanced technology, and the issue of device production should not be taken for granted.

While for low-noise and highest sensitivity applications, mK environments are essential, also high-Tc superconductors (such as MgB_2 [103]) can play an important role, in particular through their very high sensitivity to even low energy deposits, e.g. as ultra-fast tracking detectors in high charged particle multiplicity environments [104] or as part of searches for high mass milli-charged particles. In such an application, coincidences or anti-coincidences between devices can overcome random signals.

work package	clocks & networks	super-conducting	kinetic sensors	atoms/ions/ molecules	opto-mechanical	nano-engineered / low-dimensional
WP-3a (4K stage)		X	X		(X)	(X)
WP-3b (detection)		X				
WP-3c (integration)		X				

Table 7. Quantum sensor families impacted by R&D in WP-3

7.1 Physics drivers

From the point of view of particle and fundamental physics, the extreme sensitivity of superconducting detectors, whose unprecedented sensitivity is provided by the O(meV) energy required to break Cooper pairs, or by exploiting the long-range order of the coherent superconducting state, is well matched to very low-energy phenomena. Also, quantum-noise-limited amplifiers and frequency converters from microwave to submillimetre wavelengths are entirely feasible. More exotically, squeezed superconducting amplifiers achieving noise temperatures well below the quantum limit have also been demonstrated at microwave wavelengths, opening the door to numerous applications. Homodyne detection methods based on superconducting chip electronics operating over RF bandwidths up to 100 GHz and achieving quantum-noise-limited sensitivity are also being developed. Superconducting devices are thus highly promising and, in fact, an essential part of ultra-light dark matter detection and measuring the mass scale of the neutrino.

Many international collaborations seek to build instruments capable of detecting axions and dark photons through their conversion to microwave and millimetre-wave photons in strong static magnetic fields (1-10 T). Numerous experiments are being devised and built, but all of these rely on the existence and further development of superconducting detectors and readout electronics of one kind or another. Thus, superconducting microcircuit technology is an essential part of enabling this whole community.

It is well known from neutrino oscillation experiments that neutrinos have mass, but the absolute mass scale is unknown, and this remains one of the most important challenges in particle physics. A very promising approach, the principles of which have been demonstrated by Project 8 in the USA and are now being pursued by QTNM in the UK, involves measuring the end-point spectrum at 18.6 keV of the electrons released during the beta decay of atomic tritium. This is achieved by circulating the tritium through a 1 T static magnetic field and observing the cyclotron radiation of the mildly relativistic ($\beta = 0.25$) decay electrons: Cyclotron Radiation Emission Spectroscopy (CRES). The end-point single-electron events are, however, infrequent, short lived (due to scattering and radiative decay), and the amounts of RF power radiated tiny ($<$ 1 fW). Thus, large arrays of ultra-sensitive, ideally quantum-noise-limited, microwave antennas and receivers is needed. The whole subject of realising ultra-sensitive inward looking phased arrays and spectrometers for monitoring the dynamics of individual radioactively released electrons is now an active area of study. From a physics perspective, the method is already looking highly feasible and achieving energy resolutions of much less than 100 meV. Thus, although measuring the absolute neutrino mass is extremely challenging, aiming to detect an extremely tiny spectral distortion in the end-point region of beta and electron capture spectra at an energy scale much less than 1 eV is very well motivated given that we know that there is a lower bound for neutrino masses.

Another application of the use of superconducting devices is the study of coherent elastic neutrino nucleus scattering or the search for dark matter through nuclear recoils. The energy transfers in these processes are expected to be tiny and ultra-sensitive instruments are required to detect a signal for which these detectors seem uniquely suited.

Areas such as combining superconducting devices with micro-machined accelerometers and mechanical resonators, including highly-sensitive levitated (opto-)mechanical devices, are largely untouched but entirely realistic. Combining superconducting devices with single or macroscopic spin systems (see WP-4a) is an area that is also starting to gain traction, and will invariably lead to major innovations. It appears that the application of superconducting devices to massive particle detection has not been explored in-depth or indeed exploited, but there is a steady trickle of disconnected papers in the open literature going back for many years on this topic. Finally, to our knowledge, there have been no published quantitative studies exploring the application of superconducting devices and electronics to traditional accelerator-based particle physics experiments, and this is clearly a subject of substantial importance. In all these areas, advances in the devices themselves (WP-3b), in the requisite electronics (WP-3a) or in the integration into easily usable devices (WP-3c) are required.

In summary, numerous opportunities exist for creating a new generation of fundamental physics experiments based on superconducting devices and electronics (there is some overlap with DRD7 in this later area). The developments needed are at multiple levels: (i) innovating the experiments and instruments themselves, carrying out performance calculations where needed; (ii) designing instruments at a systems level taking into account the new challenges of achieving quantum-noise limited performance, which introduces the whole new domain of quantum systems engineering; (iii) innovating, designing, fabricating and characterising the various different forms of superconducting electronics needed for the different experiments; (iv) increasing the TRL to science grade, as distinct from research-grade, of fully packaged components and sub-systems that can be used reliably by instrumentalists who are not themselves interested in the intricacies of device physics.

With a focus on the intermediate TRL developments, the following technologies have been targeted:

- Materials science and device processing methods and techniques.
- Quantum-noise-limited parametric amplifiers for microwave and millimetre-wave frequencies: both of the travelling-wave type, for wideband applications, and resonator amplifiers for the most demanding narrow band applications. Ultra-low-noise amplifiers for generating and amplifying squeezed states. High operating temperature (4K), arrayable, low-noise, high dynamic range amplifiers to eliminate the need for cryogenic transistor amplifiers completely, where large-format systems are needed.
- Ultra-sensitive power detectors pushing into and below noise equivalent powers (NEPs) of 10^{-20} $\mathrm{WHz}^{-1/2}$. Integrated chip-based balanced-homodyne systems from microwave to submillimeter-wave frequencies.
- Single photon detection; particularly at microwave and millimetre-wave frequencies, where the energies are low, and photon counting is challenging. There is some overlap with DRD4 in this area.
- Solid-state superconducting detectors for low-energy and moderate-energy massive particle detection and spectroscopy, such as single-electron and ion detection and beam-statistics characterisation.
- Multiplexing technology for superconducting mega-pixel devices of various kinds.
- Development of packaging methods for superconducting electronics: EMI shielding, magnetic field shielding, cosmic ray shielding, stray light shielding, operation in harsh environments, cryo-mechanical interfaces including well-engineered thermal uniformity and temperature stability throughout all levels of the packaging. Precise thermal design is often overlooked, but essential.

These activities have been grouped into three areas around which the three sub-WP's of the superconducting WP are arranged:

- Theme 1: Superconducting electronics for the microwave to millimetre-wave range.
- Theme 2: Low and high-energy particle detection (photons & massive particles)
- Theme 3: Characterization and measurement methods, including packaging and shielding techniques for reliable operation in harsh and demanding environments.

It should be stressed that various developments needed for the various device types have a considerable amount in common: materials and microcircuit processing, device modeling and non-equilibrium superconducting physics, understanding second-order solid-state physical processes such as noise and anomalous heat capacity, packaging, cryogenic engineering and readout methods, and test and characterisation. As an example for Theme 2, but also to emphasise the inter-relatedness of the three themes, we consider the case of TES/KIDs:

- The optimization of TES/KID based light detectors to further enhance their sensitivity, including consideration of the Neganov-Trofimov-Luke effect, and the control of solid-state time constants and timing resolution through the investigation of novel materials and geometries. Understanding the microscopic processes by which superconducting devices can unexpectedly store heat, thereby leading to increased time constants and slow devices is a topic of considerable importance. Understanding how to make TESs and KIDs that operate at temperatures below 50 mK, where new physics often comes into play, is also a topic of considerable interest.

- Establishing methods for fabricating large arrays of devices to enable the realization of complex microcircuits that have increased functionality, such as chip-based microwave homodyne detectors.

- The development of compact multi-way cryogenic wiring with exceeding high levels of EMI rejection, low levels of crosstalk, and low levels of acoustic pick up. We underline that, in contrast to TESs, KIDs are currently operated using the same readout as superconducting qubits, i.e., printed circuit boards, SMA connectors, coaxial cables for RF applications, that are known to be intrinsically radioactive, rigid (with potential impact on vibrations) and large.

- The development of multiplexed readout for TESs, to minimize the number of channels and the heat load on the cryostat. This will not be as necessary for KIDs, that are naturally multiplexed, even if a study on the number of detectors that can be coupled to the same feedline without impact on the performance, is still mandatory.

- New DAQ/storage/trigger systems to deal with the much higher data rate of these fast sensors compared to the standard cryogenic calorimeters.

It should be noted that because of customization costs and a relatively small user base, these developments will not be driven by industry. However, the fundamental techniques and technologies developed would have a substantial and transformative impact on other practical applications: quantum communications, quantum computing, quantum radar, and passive monitoring, such as security body scanning. This applies not only to the devices themselves, but to other areas of development such as generic quantum system engineering and ultra-low-noise system modelling.

7.2 WP-3a: The 4K stage

The whole matter of how to multiplex and read out superconducting electronics requires special attention. Each of the individual device types uses and indeed needs its own readout techniques: TESs, for example, use SQUIDs, and KIDs use high-electron-mobility-transistor (HEMT) amplifiers. The crucial point is that the readout method is almost always a key part of achieving the ultra-low-noise operation that the device is intrinsically capable of achieving. The primary device and the readout system must be designed together as an integrated whole. In fact, in many devices, TESs that are read out with SQUIDs, for example, even the wiring between the primary device and the readout components, must be superconducting throughout. Here, too, major innovation and development is needed. For example, KIDs and SIS mixers are read out using cryogenically cooled HEMT amplifiers. The noise performance of the readout amplifier is critical in determining whether the absolute performance is achieved overall. But HEMT amplifiers are large and expensive and cannot be produced in volume, and so some groups are starting to look at reading out these superconducting devices with superconducting parametric amplifiers, which can be reproduced lithographically in large volume and can be quantum-noise-limited themselves. Some devices would benefit enormously from the development of cryogenic ASICs, operating at 4K, and indeed this is an active area of research in the community[*].

Advancing the integration of electronics in proximity to quantum systems with the aim of reducing the complexity of the designs, improving the thermal footprint and increasing the stability and scalability of the devices necessitates the operation within the realm of limited power dissipation at liquid helium temperatures.

Presently available tools for designing and simulation of the behavior of components fall short of encompassing cryogenic conditions. The location of anomalies in the behavior as a function of temperature of components mandates specific measurements. In areas as beam control and monitoring properties of different components were investigated in LHe conditions finding elements that can withstand the environment.

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[*] e.g. Horse Ridge II by Intel: https://www.intel.com/content/www/us/en/newsroom/news/2nd-gen-horse-ridge-cryogenic-quantum-control-chip.html

Frontier experiments will gain significantly from a diversified spectrum of elements adaptable for deployment within cryostats, SRF cavities, or using ultracold He as detectors. To achieve the community's goals, elements such as arrays of parametric amplifiers, ASICS at 4K (down to 28 nm), FPGAs are needed. Furthermore, complementing these elements with tunable circuit elements along with a more profound comprehension of material science considerations at 4K are needed.

Kinetic-inductance travelling-wave parametric amplifiers (KI-TWPA's) are well suited to read-out of multiple cryogenic detectors (TESs, MMCs, cavities), for example for neutrino mass experiments. TWPA potentially offer large bandwidth and noise close to quantum limit. KI-TWPAs can surpass J-TWPAs thanks to high dynamic range, resilience to magnetic field and possibility to operate them at higher temperature ($\sim$4K).

The community will benefit from having:

- A detailed library of validated methodologies and devices at 4K, including ASICs, primitives, IP blocks, COTS components; accompanied by a precise location of anomalies.
- Establishment of standardized setups and testing facilities with LHe/refrigerators.
- Facilitated accessibility to the production and iterative refinement of ASICs for rigorous assessments within the 4K domain.
- Whilst different devices have different needs, there is a clear benefit in terms of standardization, both in terms of the production of the ASICs themselves, but also in terms of the Real-time software.

7.3 WP-3b: Cryogenic quantum sensors for particle and photon detection

This WP forms the core of a superconducting device development programme, and again emphasises some of the key areas that would need to be addressed.

Single-photon and quantum-noise-limited detection in the microwave range holds the promise of speeding up light dark matter searches in the range above a few GHz and up to around 20 GHz [105], where the projected scan rates to probe the parameter space of interest are too low with state-of-the-art resonant cavity detectors, translating to several hundred years to scan a decade in mass at relevant sensitivity. This limitation is intrinsic to the haloscope approach, calling for long integration times at each probed frequency (i.e. particle mass) because the signal is much smaller than the noise that is of quantum nature if the signal is readout with linear amplifiers at the Standard Quantum Limit (SQL). Ideally, the scan speed enhancement given by the adoption of a photon counter for cavity signal readout is exponential in $h\nu/kT$, giving for instance 10^4 gain with a resonator at $\nu = 10\,\mathrm{GHz}$ at typical 50 mK dilution refrigerator temperature. In real power-measuring devices and counters, the quantum advantage is set by (i) the quantum noise temperature which is an inevitable consequence of the quantum trade off between measuring amplitude and phase when a signal is amplified; (ii) the level of dark counts recorded in absence of signal photons, which in recent realizations has been reduced to the few tens of Hz required to make these searches possible in a manageable amount of time. Detection of $10^{-22}\,\mathrm{W/Hz^{1/2}}$ signals is demanding but feasible.

Ultra-sensitive detection schemes at microwave frequencies play a central role in quantum sensing. In many applications, the necessity of reading a large array of devices (e.g. detectors and cavities) calls for large bandwidth amplifiers with the lowest possible noise. A leading proposal for achieving broadband bandwidth and noise at the standard quantum limit is through the use of a traveling wave parametric amplifier (TWPA) such as the Josephson JTWPA [106] or a kinetic inductance KI-TWPA [107]. KI-TWPAs provide several key advantages, such as high dynamic range around -60 dBm [108], resilience to high magnetic fields [109], possibility to be operated over a large range of temperatures [110] (from millikelvin to 4 K), and simple microfabrication, requiring only a few lithography and etching steps, without overlapping structures. Moreover, the amplification bandwidth can be tuned to cover different ranges up to 100 GHz, including the C (4–8 GHz) X (8–12 GHz), K (12-40 GHz), V

(40-75 GHz), and W (75-110 GHz) radio bands. Developments in these areas are also relevant for WP-4a and WP-4c.

While already a mature technology in the field of observational astronomy [111] and neutrino physics [112, 113], quantum sensing detectors like transition edge sensors (TES) and magnetic microcalorimeters (MMC), and kinetic inductance detectors (KID) are relatively new to the field of particle detection and open up new possibilities for exotic beam physics because they offer, for the first time, high sensitivity and high efficiency. However, in these fields, so far, these technologies are nascent and have been principally used in metrological situations, and further development is needed to make them broadly and easily applicable to exotic beam physics. For example, first deployment of x-ray TES detectors with muonic [114], pionic [115] , and kaonic [116] beams have shown promising results, but also highlighted the current limitations coming from coincident charged-particle background and limited understanding of the detector response functions. Similarly, applications of superconducting detectors for neutrons (either incorporating converters or using e.g. MgB_2) are not yet a mature technology [117].

There are several tasks to be undertaken to make these new detector technologies compatible with future needs for exotic beam physics, among them:

- Coincidence detectors : Development of a cryogenic charged particle anti-coincidence detector for use with microcalorimeters. This step is essential to reduce beam-induced background and will be useful both for exotic beams like heavy ion storage rings and muon beams, and space-based detectors or superconducting x-ray detectors that will be deployed in the ESA ATHENA project, but also for precision spectroscopy of exotic atoms.
- Exploration of the use of high T_C SNSPD-like detectors for easier integration in existing and future cryogenic (but not necessarily sub-K) environments, such as beam dump or high particle multiplicity environments (requiring e.g. high particle sensitivity or high temporal resolution).
- Metrological calibration lines above 50 keV to 300 keV, needed for high-precision measurements with TES/MMCs whose non-linear response function requires well-known calibration lines close to the transitions of interest. Exact line shapes have been obtained for example by using x-ray tubes with crystal spectrometers [118], but currently these highest-precision calibration lines are limited to the few tens of keV regime and limited high precision calibration lines are available in the few hundred keV regime. In principle this can be obtained from both radioactive sources and highly-charged ion transitions measured with crystal spectrometers, but a coordinated effort is needed between the highly-charged ion community and gamma ray sources to provide a dedicated set of calibration lines in the hard x-ray and gamma-ray regime.
- Microcalorimeter detectors are very sensitive thermometers, and any phenomenon that heats the detector arrays can shift the response function of the detector and introduce systematic shifts. The effect of charged-particle hits has been studied experimentally, but a full modeling of charged particle background from source to detector would allow to unambiguously disentangle this important contribution to the signal and enable more precise measurements. A dedicated full theoretical study would benefit all microcalorimeter detectors and current and future precision studies with charged particle beams.

In parallel with the above device developments, continuous benchmarking against experimentally relevant criteria is crucial, and represents a device-independent requirement. The milestones will thus emphasize this aspect, but it is understood that development of multiple device types is assumed to occur in parallel.

7.4 WP 3c: Resilient integration of superconducting systems

To date, considerable emphasis has been placed on understanding the physics of new devices and developing sophisticated methods for manufacturing them, but a crucial area of study that has received little attention so far, except in the context of placing superconducting devices in space-based instruments, is the whole matter of packaging and integration. Superconducting devices are, by their very nature, highly sensitive devices, but this means they can be highly sensitive to extraneous influences, in addition to being sensitive to their primary target. For example:

- Many devices are low impedance (such as the TES readout lines), and the superconducting wiring is extremely low impedance, which means that unintended currents can be induced easily by EMI or by vibration caused by the wiring moving through intended or unintended static magnetic fields - such as screws having magnetic impurities.
- Many fundamental physics experiments, such as axion experiments and neutrino mass measurements, require superconducting devices to work in high static magnetic fields. But static fields suppress the energy gap of superconductors, and so change behaviour.
- If a static field is present on a superconductor when it is cooled through its transition temperature, magnetic vortices can become trapped, completely changing performance. Moreover, when RF currents are applied as part of a device's operation, the vortices can then move, leading to a loss mechanism.
- Particle-detecting superconducting devices can be sensitive to background infrared radiation far removed from the detection energy of interest. Long-wavelength stray light at mm-wavelengths inadvertently coupling into devices intended for FIR astronomy (200-20 μm) has been an enduring problem of considerable difficulty. This stray light can act as a loading, and can also introduce noise of its own.
- It is often assumed that the temperature of the superconducting device can vary without affecting the operation of the device appreciably, but this is rarely true. In many devices, the application of DC or RF power that must be applied as part of the device's primary operation (such as the readout pump for KIDs and the drive pump for parametric amplifiers) can slightly heat the device, leading to a degradation of behaviour. Additionally, the temperature of the fridge itself may fluctuate at the μK and nK level, and this is sufficient to act as a noise that dominates all of the assumed noise sources. An unexpected mechanism, which has been found to affect behaviour, is where the heating of a nearby bias resistor puts IR into a box that is then seen with a long time constant by a superconducting infrared detector array.
- How should delicate chips be mounted in packaging to ensure good thermal coupling of the chips to the device's box: epoxy, clamps? There are many issues here, such as the outgassing of certain epoxies affecting the time-constants of devices and, in some cases, the need for extreme optical alignment and flatness.
- Numerous different extraneous processes can cause instability, which gives rise to 1/f noise in the output of a device, preventing the intrinsic behaviour from being reached, and limiting integration time.
- In some applications, the effects of seeing secondary electrons from cosmic ray hits in parts of the packaging, and indeed in the Si wafers themselves, becomes a considerable challenge. This has been witnessed many times and, in some applications, is a problem that needs addressing.

The bottom line is that considerable effort is needed to turn devices that are intrinsically capable of extreme sensitivity into devices that actually achieve extreme sensitivity in harsh environments in a reliable way. Thus, understanding how to package, mount, wire, shield, and cool superconducting devices becomes an essential study in its own right. We have dedicated a whole theme to this subject, which we feel is neglected, and yet cuts across achieving high TRL in all of the superconducting devices needed and considered.

7.5 Milestones and deliverables WP-3 (years 1 / 3 / 5)

Milestones are underlined, deliverables are in *italic.*

WP-3 (Cryogenic systems)

WP3a	→ design 4K ASIC	→ fabrication 4K ASIC	→ library release
(electronics at the 4K stage)	*tape-out*	*4K ASIC*	*library*
WP3b	→ prototype beam tests	→ specifications	→ integration in experiment
(calorimetry, tracking)	*characterization*	*Test Beam*	*Operation of multi-channel SC detector in beam*
WP3c	→ identification of challenges	→ specification	→ delivery
(resilient integration)	*System design*	*Readout developed*	*Multi-channel detector system*

Example 1: Ultra-low-noise thin-film superconducting devices are central to the advanced of numerous areas of fundamental physics, and considerable opportunities for innovation exist. For example, the homodyne technique is used extensively in quantum optics experiments, but has not been realised at microwave and millimetre wavelengths. It is entirely realistic to fabricate chip-based homodyne detectors, where all power detectors and RF components are integrated on a single thin-film device. These devices will operate in the classical to quantum transition, and could find extensive use in low-noise microwave/millimetre/submillimetre-wave spectroscopy of the kind needed for ultra-light dark matter searches, such as axions. This would make a significant innovative contribution to axion experiments.

Example 2: Hybrid systems with magnetic levitation and superconducting technologies can lead to excellent sensors of acceleration, forces and electromagnetic fields, which can for instance be applied to dark matter search experiments. SQUID-coupled devices, for example, can also be used for sensitive readout or in hybrid optical-electro-mechanical approaches.

Example 3: SNSPDs exhibit superb position and timing resolution with very low background count, short reset times and excellent efficiency. Thin film technologies for high T_C superconductors open up the possibility of operating corresponding superconductor-based quantum sensors at easily accessible temperature ranges that do not require dilution refrigerators. Already now, MgB_2-based SNSPDs operate at temperatures higher than 10 K. Using them as tracking detectors could open up new areas of application such as deployment in Roman Pot detectors for forward physics or as luminometers measuring Bhabha scattering for FCC experiments, in which the demands on detector performance are high, but the scale of the system is limited, or as tracking detectors for high-energy milli-charged particles.

8. WP-4: SCALING UP “QUANTUM”

Typical quantum sensing systems are at or below the nanometer or single sensor scale. For high energy physics applications but also for enhanced sensitivity of e.g. levitated macroscopic systems, nanofabricated accelerometers [119], or opto-mechanical and cavity-based dark matter [120] and gravitational wave searches, scaling up to much larger dimensions than is currently feasible is needed. In this Work Package, the challenge of incorporating quantum systems in large-scale devices without losing their (local) quantum behavior will be tackled. This can require manipulating bulk matter, such as NV-diamonds, ferro-electric materials or gases, liquids or solids with spin-polarized nuclei or electrons, in such a manner that a very large fraction of the spins are aligned. It also can require incorporating individual quantum systems such as quantum dots in bulk systems, such as scintillating materials. Another aspect of scaling up quantum systems is constructing very large surface areas or "target volume" Superconducting Nanowire Single Photon Detectors [121], graphene mono-layers [122] or constructing or engineering materials at the nano-scale such that local quantum behavior results in desired properties such as those of engineered multi-layer heterostructures. Heterodox approaches that would combine established technologies from different fields, such as Quantum Cascade lasers with silicon position sensitive detectors, or incorporating scintillating nanodots into tracking devices (DotPix) [123] can potentially lead to new or enhanced capabilities for detection and characterization of particles at high energies.

work package	clocks & networks	supercon-ducting	kinetic sensors	atoms/ions /molecules	opto-mechanical	nano-engineered / low-dimensional
WP-4a (spin ensembles)		X	X	X	X	X
WP-4b (hybrid devices)					(X)	X
WP-4c (opto-mech. sensors)					X	

Table 8. Quantum sensor families impacted by R&D in WP-4

8.1 WP-4a: Massive spin polarized ensembles

Three overarching categories of massive spin-based detectors have been considered:

- Levitated ferromagnetic torque sensors (overlaps with spinor BEC and optomechanical accelerometer)
- Molecules with radioisotopes for EDM searches
- Large volume, high density, highly spin-polarized samples (for HEP and exotic spin-dependent samples, but also magnons)

Where are we? What needs to happen?

The first category is sensitive to local sources or ultra-low energy bosonic fields. Spin samples with long coherence times such as ferromagnetic particles (10 μm particulates floated in vacuum at 10 mK) should be many orders of magnitude more sensitive than existing systems (e.g. NVD, BEC). Arrays of these micro-particulates should be possible. A consortium of groups in Europe and US collaborators working on this category exists. NV diamond spin manipulation measurement and control also plays a role in proposals to search for entanglement induced by gravitational interactions as a probe of the low energy interplay between quantum mechanics and gravity (this approach is relevant for WP-4c, in the form of ensembles of diamonds with a single NV center in each diamond) but also as a potential pathway for bulk-"polarized" materials).

What is needed is the development of beyond state-of-the-art (superconducting) readout electronics, much better vacuum and purity/flux trapping of superconductors for suspending/levitating the bulk samples. Both the existing community and large-scale HEP labs have quite some expertise in the required areas.

The second category concerns molecules with radionuclides for eEDM searches, with a reach in terms of BSM sensitivity beyond 10 TeV masses. Given the overlap with WP 1 (exotic systems in traps and beams), this category, dealing mainly with small numbers of probed molecules, is subsumed under WP 1, although in specific cases, bulk amounts of such spin-oriented molecules are needed.

The third category of production of high-density, polarized ”targets” and CASPEr-like experiments benefit from large compact samples of spin polarized systems. Going to lower temperatures (from 4K down to 10mK) and to larger sample sizes (from mm to 10 cm) is important. The following is being looked at and in need of development: expansion of the range of species (other species in addition to para-hydrogen); dynamic nuclear polarization (CASPEr-E with ferroelectric crystals); optical polarization, polarized LXe, Liquid ^{3}He, naphthalene, and others. In many cases, this requires advances in solid state physics, chemistry, etc., so there is a need to enable supporting developments in neighboring fields and encourage mutual exchange (WP-6b). Additionally, fifth force spin dependent experiments employing spin polarized samples such as QUAX-$g_p g_s$ [124] and ARIADNE [125] would greatly benefit from improved methods of producing and manipulating hyper-polarized spin samples such as ^{3}He, including spin squeezing in the future. In this context, the usefulness of bulk electron- or nuclear-spin polarized materials (such as NV-diamonds) for helicity-sensitive tracking devices, relevant also for nuclear physics, requires further R&D on hyper-polarization, as well as beam tests for establishing proof-of-principle (WP-6c).

8.2 WP-4b: Hybrid devices

The building blocks of the devices that are envisaged within this WP are partially addressed in the framework of WP-2a. The challenge that is the focus of this WP is their incorporation in macroscopic devices such that their quantum properties are gainfully maintained.

8.2.1 WP-4b_a: Scintillators

While scintillating materials are the subject of specific R&D for calorimetry (DRD6) and for photon detection (DRD4), the scintillation behavior of systems consisting of small numbers of atoms results in drastically different behavior that justifies a dedicated WP. Confinement results in artificial atoms, such that nanowires, nanoplatelets, mono-layers, quantum dots, quantum wells, and other structures or heterostructures at the few nm scale have well defined properties amenable to nano-engineering. Of particular interest are rapid rise and decay times, narrow-band emission spectra, tailorable via composition, geometry and size, and the breadth of systems that allows optimizing their overall properties when incorporating them. Novel active scintillators, based on e.g. quantum wells, would enable novel functionalities.

Other nanostructured materials with similar potential include metal organic frameworks, aerogel / scintillator hybrid structures, e.g. YAG aerogel with high porosity, supercrystals, optically suspended nanospheres; HfO_2-loaded (high density) water, and many others.

Where are we? What needs to happen?

Stopping power is important for high energy physics experiments, so micromachining or engineering of a mix of bulk and nanomaterials is required. Similarly, determining the resistance of any novel materials to radiation is a crucial step in evaluating their potential and suitability for a specific application. Developments both in the field of optics (e.g. metalenses) and large-scale integration (integration of heterostructures) are needed to achieve the transition from small numbers of devices with low amounts of energy deposited by minimum ionising particles to massive devices with high stopping power.

8.2.2 WP 4b_b: Ensembles of heterostructures

Composite structures combining low-dimensional materials and nanostructures with established detector technologies can offer unprecedented tunability and improvements in detector sensitivity and performance compared to conventional bulk materials. Work function (WF) engineering may allow for increased Quantum efficiencies (QE) with examples being demonstrated by composite photocathodes with coatings of atomicially thin graphene or boron nitride (BN). Graphene monolayers on photocathodes *increase* the WF, thus enhancing emissivity, while BN can *decrease* the WF and increase QE. Different nanowire systems have been proposed as high efficiency photocathodes owing both to improved geometric emission probability as a result of their large surface to volume ratios as well as their reduced dimensionality. In addition to enhanced sensitivity, low-dimensional materials may also be used to tune the response spectrum by either exploiting resonance effects (e.g. quantum dot size chosen in view of enhanced sensitivity to specific wavelength) or using systems that can cover a broad wavelength region such as twisted bi-layer graphene.

In gaseous detectors, low-dimensional materials may be used to fine-tune charge transport processes to address limitations of conventional gas-based detectors. This may include the suppression of ion backflow with single- or few-layer suspended graphene membranes acting as selective ion filter while allowing for electrons to pass. Such layers may also be used as physical barrier to a separate gas volume allowing for a choice of optimal gases for the sensitive and amplification regions of a detector.

8.2.3 WP-4b_c: Heterodox devices

Combinations of different technologies may result in redundancy, enhanced sensitivity, complementarity, but possibly also in completely new functionalities. By their sub-micron dimensions, quantum components have the potential to be incorporated within, form a layer on, or result in an ordered sub-structuring of existing devices and their sensitive elements. In this sense, developing further devices like DotPix [123], investigation of the feasibility of coupling of silicon detectors to Quantum Cascade Lasers, or considering sub-micron charged particle position detection through spatially-ordered nanodots (as scintillators) within the pitch of a silicon strip detector, are the type of developments envisaged in this WP. Also opto-mechanical sensors, in which the force acting on a mechanical system is transduced to a measurable optical signal, fall in the category of devices leveraging different behaviors in different modalities.

While initially, such heterodox approaches will need to be developed at the individual sensor scale, their usefulness to e.g. high energy particle tracking or identification requires being able to produce and operate them at large scales or in large numbers.

Given the nature of this WP, it connects directly not only to other work packages in RDq, but also to other DRDs. Arrays of opto-mechanical sensors, for example, connect directly to WP1 that addresses networking of clocks. Large systems of superconducting devices tie to WP2 for the development of materials. Readout, sometimes at low temperatures, connects to DRD7 that advances electronics. Superconducting nano-wire photodetectors closely connect to the efforts within DRD4 and quantum-enhanced scintillators tie directly to calorimetry, that is covered by DRD6.

Where are we? What needs to happen?

There is, to some extent, an overlap with WP-2b, given that that WP focuses on expanding the kinds of building blocks with novel or extended existing functionalities for detectors. In contrast, this WP focuses on combining (novel) building blocks with different functionalities with the expectation that their interplay will, in turn result in additional novel or extended existing functionalities for detectors.

While a number of promising materials and structures have thus been proposed and experimentally evaluated, implementing them in detectors relevant for e.g. HEP detection needs poses a number of challenges. Most notably, the mismatch in size scales between nanofabrication techniques and detection areas required for future experiments necessitates dedicated collaborative efforts of material researchers and detector developers. Additionally, compatibility with and stability of low-dimensional and nanostructured materials in environments encountered in HEP detector systems needs to be studied and evaluated.

Also here, a collaborative framework bringing together communities of material scientists and detector developers would be highly beneficial to share knowledge and experience on materials and systems with potential applications for future detection needs. Dedicated meetings and workshops, expert contacts and databases of materials of interest as well as common organisation of measurement campaigns can be valuable aspects to bridge the gap between novel materials and their application in relevant future detection systems. It is however of particular importance for this WP that these workshops are targeted at, and attended by, a heterogeneous sample of experts.

8.3 WP-4c: Opto-Mechanical Sensors

Mechanical systems have long been used for precise measurements of displacement, force, acceleration, magnetic and electric fields. These systems offer the capability of scaling to a macroscopic mass, as required for several high-energy physics applications, whose motion can be read optically, making them compatible with quantum sensing approaches developed in the quantum information science community (see WP-5) to further enhance their sensitivity.

Extensive research has identified the quantum measurement based limits of optical and electrical readout of individual mechanical sensors. This is often referred to as the standard quantum limit (see WP-5 for further details) and incorporates the inherent uncertainties associated in the bosonic degrees of freedom (i.e. optical, electrical, mechanical) along with backaction noise resulting from their mutual interaction [126, 127]. With recent technological advances, the ability to perform at or beyond the standard quantum limit of measurements on individual mechanical sensors is now widely accessible, ushering in a realm of sensors that have revolutionized technological capabilities. For example, atomic force microscopy relies on quantum-limited optical readout to measure deflections of a cantilever interacting with a sample. This technology has been widely adopted by the semiconductor industry and is critical for characterisation of nanofabrication processes. A more recent example is that of levitated nanospheres, whose centre-of-mass motion can be optically detected to enable zeptonewton (10^{-21} N) force sensing [128]. This capability out-performs conventional room-temperature force sensors by over an order of magnitude and enables a variety of applications including electric-field sensing, inertial sensing, and gravimetry.

Here, we highlight macroscopic opto-mechanical sensing elements as emerging systems for probing novel fundamental physics. Indeed, opto-mechanical based strain and acceleration sensors can play a significant role in the search for Beyond Standard Model (BSM) physics, including dark matter [7, 119, 129–135], neutrinos [136], gravitational waves [9, 10, 137, 138] and tests of Lorentz symmetry [139]. Examples of promising quantum technologies include resonant mass detectors, where the materials can vary from low-loss solids [132, 134], levitated particles, MEMS, and novel approaches such as superfluid Helium based sensors [140, 141].

Where are we? What needs to happen?

Research and development is needed to optimize the sensitivity, design, and readout of opto-mechanical sensors to reach the sensitivity limits required for particle physics applications. While measurements at the standard quantum limit have been demonstrated for individual opto-mechanical sensors, quantum sensing techniques are needed to push them beyond this limit. Extending from a single sensor to a network, perhaps with entanglement, will be a challenging but critical step towards discovering new physics, with initial experimental results being reported recently [142].

8.4 Milestones and deliverables WP-4 (years 1 / 3 / 5)

Milestones are underlined, deliverables are in *italic*.

WP-4a (spin-polarized ensembles)

WP4a ⟶ map of polarizable systems → better polarizability → bulk high polarization
workshop/report *prototype*

WP-4b (Hybrid systems)

WP4b_a ⟶ overview of technologies → focus on HEP-relevance ⟶ lab/beam tests
(Engineering at the nanoscale) *report* *downselect*
WP4b_b ⟶ tests of existing blocks ⟶ engineering proposals ⟶ prototype tests
(bulk heterostructures) *report: outcomes/challenges*
WP4b_c ⟶ conceptual studies ⟶ feasibility studies ⟶ prototypes
(heterodox devices) *workshop on device concepts*

WP-4c (opto-mechanical sensors)

WP4c ⟶ sensor optimization ⟶ coherent interconnects → quantum network
workshop

Example 1: Optomechanical systems are currently utilized for highly sensitive measurements of displacement, force, acceleration, magnetic and electric fields. Over the last decade, innovative strategies employing non-classical measurement techniques have been shown to surpass the standard quantum limit of individual sensors. Networking such systems together opens up the possibility of further enhancements through collective measurements of multiple quantum-coherent sensors, as demonstrated by Ref. [142]. However, the optimal configuration and fundamental limits to collective measurements within networks of quantum-coherent sensors remain relatively unexplored, as does their application to searches of physics beyond the standard model.

Example 2: Theoretical investigations have shown that measuring the gravitational field of the LHC beam should be within reach of single quantum-optomechanical sensors in the near future [143]. This enables a new lab-scale test of General Relativity on mm-range distances, where the source of gravity is almost pure kinetic energy rather than mass. On a medium- to long-term perspective, when cooled and possibly squeezed particle beams become available, it might also allow measuring the gravitational field of matter in a non-trivial quantum superposition. However, technical constraints might require a larger distance of the sensor from the beam with correspondingly smaller gravitational acceleration. In this case, a network of sensors along the beam could be read out with the common mode of a laser, using “coherent averaging” [144, 145], with the signal/noise ratio being proportional to the number of sensors (see WP-5b).

9. WP-5 : QUANTUM TECHNIQUES FOR SENSING

The Heisenberg Uncertainty Principle limits the sensitivity of measurements. This limit is placed on the simultaneous measurement of two non-commuting quantities, such as the amplitude and phase of a signal, for example. This limit in sensitivity is referred to as the Standard Quantum Limit (SQL). While many experiments can reach the required sensitivities by operating at the SQL, searches of new physics and particles beyond the standard model, as well as precision measurements for fundamental constants, often require sensitivities beyond the SQL. Through the use of quantum techniques, however, one can engineer and manipulate the quantum state of a system, by making use of superposition, entanglement, squeezing and backaction evasion, to evade this SQL and thus improve the science reach of the experiments. Instruments with much higher sensitivity can be built that are able to detect tiny energy shifts in quantum systems. This work package addresses the development of quantum technologies and the theoretical framework for their application.

Work Package	clocks & networks	super-conducting	kinetic sensors	atoms/ions/ molecules	opto-mechanical	nano-engineered / low-dimensional
WP 5a (squeezing)	X			X	X	
WP 5b (back action evasion)	X			X	X	
WP 5c (entanglement)	X			X	X	
WP 5d (optimized exploration)	X	X	X	X	X	

Table 9. Quantum sensor families impacted by R&D in WP-5

9.1 WP-5a: Squeezing

To interrogate a quantum system, often light is used as a probe. Light also has a quantum description and can be manipulated for applications in sensing and metrology. One such quantum state of light is a squeezed state, which can increase the precision of optical measurements. As noted earlier, the uncertainty principle imposes a fundamental limit on the precision with which complementary quantities can be measured simultaneously. Squeezed states of light manipulate this limit by decreasing the noise in one of such quantities — say the phase (or amplitude) of the field — while simultaneously increasing the noise in the orthogonal quantity — the amplitude (or phase) of the field — hence “squeezing” the noise below the shot noise limit for some particular property of the light. This will result in a detection noise floor below the classical shot noise limit as long as the quantity being measured aligns with the quadrature that is squeezed, thus leading to a measurement having greater precision. One of the great successes is its application to gravitational wave detectors, where squeezed light is used to increase the sensitivity of the optical measurement at the output of the kilometers-long laser interferometer. In addition to gravitational wave detection, smaller-scale optical interferometers can also be used to detect strain due to wavelike dark matter [120, 146]. In this case the sensitivity is expected to be limited at high frequency by laser shot noise, and hence could benefit from the use of squeezed light techniques. Squeezed light methods can also benefit the sensitivity of other opto-mechanical resonators (see WP-4c), which can be used to search for accelerations due to vector-like ultra-light dark matter fields [119] and particle-like dark matter when scaled up to a large array [147]. Further work is needed to develop versatile and scalable sources of squeezed light, develop approaches to counteract losses and other imperfections, and demonstrate its applicability to particle physics.

9.2 WP-5b: Back action evasion

Performing a measurement implies, by necessity, interacting with the object that is measured. An important consequence of the nature of measurement is the so-called quantum back action, that is, the extraction of information from a system can give rise to a feedback effect in which the system configuration after the measurement is determined by the measurement outcome. Quantum non-demolition (QND) measurements [148] are repeated measurements of a single observable that result in no increment in uncertainty over time for the quantity of interest and yield the same precise result every time in the absence of any external influence. A quantum non-demolition measurement is accomplished when an observable is unaffected due to the quantum uncertainty produced in the corresponding non-commutative conjugate variable. A class of QND measurements is known as back-action evading measurements in which the uncertainty in the observable to be monitored is very small, at the cost of a very large uncertainty in the complementary observable.

Back-action evasion techniques have been implemented in many different experiments. A particular class of experiments of interest is impulse metrology with optomechanical sensors. Optomechanical sensors work by transducing a force acting on mechanical systems to measurable optical signals and are relevant to very sensitive force measurements that can be used to search for dark matter, for example. The effect of quantum back action typically dominates the sensitivity of a system at low frequencies, while the shot noise dominates at high frequencies. Thus, the combination of squeezed light and back-action evasion is needed to reduce the measurement-induced noise below the SQL over a broad frequency range. Demonstrations of the combination of both of these quantum techniques have already been recently implemented for the LIGO experiment [149]. In some applications, light interacts with the position of the system twice, minimizing the effect of back-action. The goal of this work package is to develop the underlying theoretical framework for implementation in experiments [150] and to perform proof-of-principle experiments to validate the theory.

9.3 WP-5c: Entanglement

While techniques such as squeezing and back action evasion offer to enable significant enhancements in sensitivities, there are applications that require or would benefit from sensitivity levels that can only be achieved with an array of sensors. In this case, an entangled network of quantum sensors can provide significant advantages, as the sensitivity of such a network scales as $1/N$ (as opposed to $1/\sqrt{N}$ for classically connected quantum sensors), where N is the number of entangled sensors [151–157], as illustrated in Figure 2. The most common way to generate entangled photons is through processes such as spontaneous parametric down conversion (SPDC) and four-wave mixing (FWM). SPDC and FWM are nonlinear optical process, where one (for PDC) or two photons (for FWM) incident on a nonlinear medium are transformed into two entangled photons. The incident photon(s) is (are) known as the “pump”, one of the output photons is known as the “signal” and the other as the “idler”. The transformation of the pump into signal and idler photons follows the conservation of energy and momentum. For applications in which a large photon flux is needed, these entangled states can be extended beyond pairs of photons into bright quantum states of light. Furthermore, the extension to more than two sensors will require the generation of quantum states of light that contain many entangled modes, i.e. multi-partite entangled states. To implement an entangled network of sensors, all of these entangled modes need to be distributed to the sensors in the network, whether locally or over long distances. Such a distribution of entanglement over a network is fraught with experimental challenges, especially when considering transmission over long distances, for which quantum repeaters are required to build large-scale quantum networks with high throughput.

One area where benefits can be expected is that of impulse metrology. Scaling in the number of entangled sensors is being pursued in this area, where the measurement of rapid and minute impulses allows for the detection of forces across a wide range of frequencies. This technique is being used e.g. to search for dark matter through its direct gravitational interaction on a mechanical resonator. In opto-mechanical sensors, the force acting on a mechanical system is transduced to a measurable optical signal. Squeezed light and back-action evasion techniques are being developed to reduce the measurement-induced noise below the SQL. Employing quantum techniques in a coherent, entangled system of quantum sensors will enable scaling of the precision proportional to the number of sensors, rather than the square root of the number of sensors.

Given the expected commensurate gains in sensitivity that can be obtained with an entangled network of sensors, the DRD5 / RDq process will seek potential proposals on how the different families of quantum sensors outlined in Table 1 can leverage developments targeted towards implementing entanglement at-scale.

9.4 WP-5d: Optimization of physics reach

Theoretical guidance will be indispensable for the implementation of quantum sensing techniques and the development of novel approaches of these techniques to particle physics. For example, the classic papers by Carl Caves and colleagues have been instrumental in incorporating quantum techniques in the LIGO experiment [158, 159]. A quantum system can generally be described by a Hamiltonian and its evolution. Each experiment has its own implementation and is susceptible to different external factors. A cavity-based axion search experiment, for example, relies on long integration times that are affected by environmental conditions. The cavity may be detuned and has an internal dissipation rate. The coupling of the signal with the cavity and its associated readout

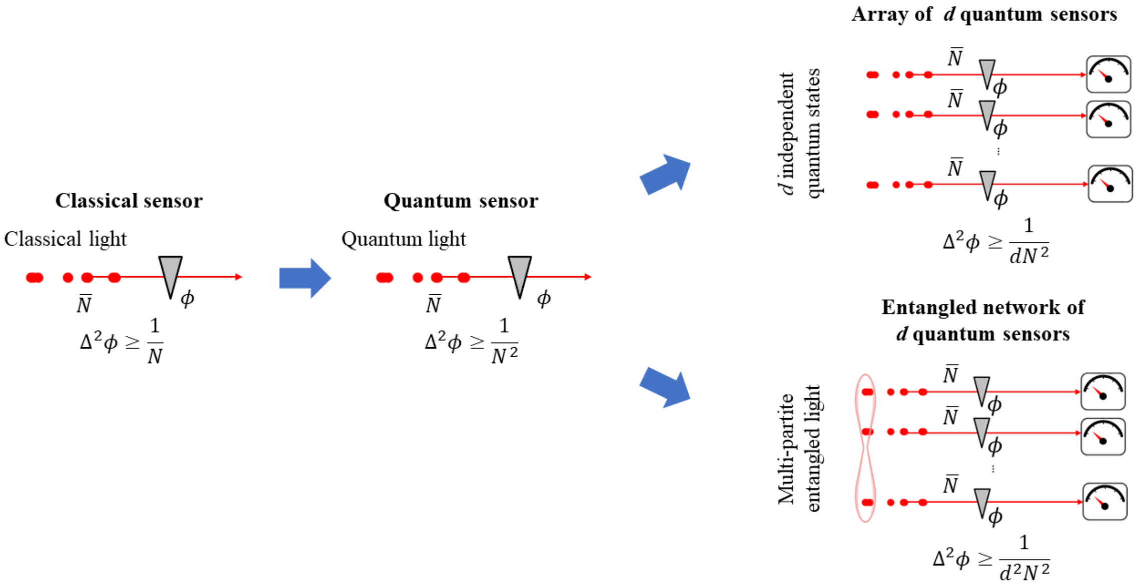
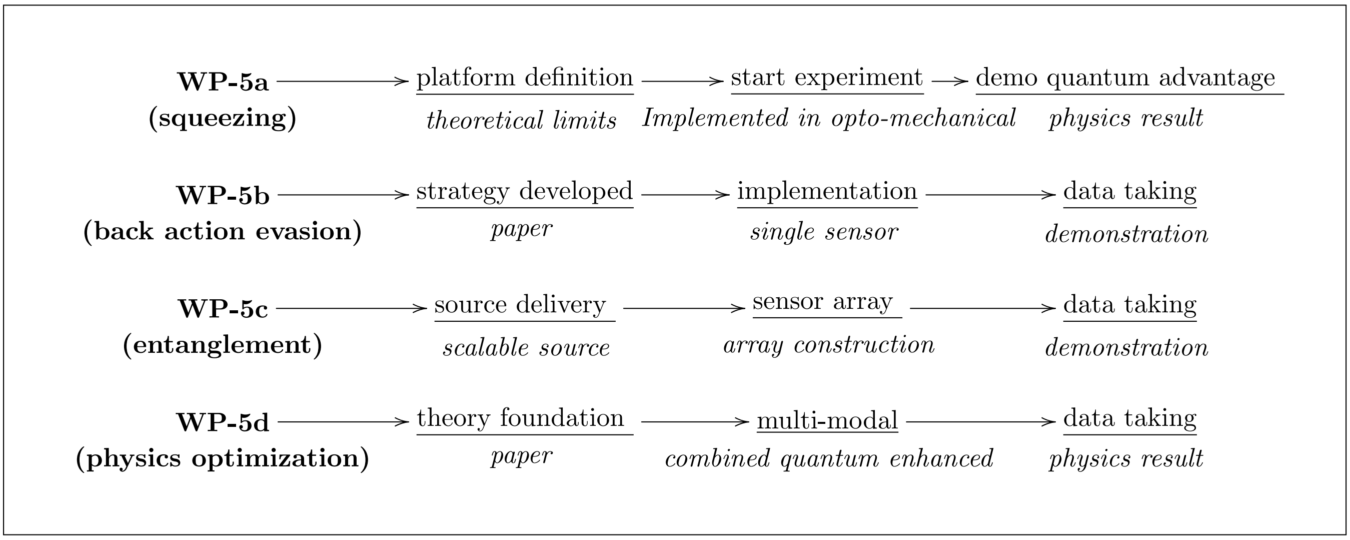


Figure 2. The improvement in sensitivity that entanglement can bring to a set of individual nodes of quantum sensors scales with the number of nodes.

depends on the specific experiment configuration. A thorough theoretical description that assesses the merits and impact of various modes of implementation of quantum techniques will be required to optimize the physics reach. In some cases, it may not be à priori evident that a combination of a squeezed light source and back-action evasion will improve the physics reach or be compatible with the experimental implementation. Additionally, fundamental sensitivity limits, as established by techniques such as the quantum Cramér-Rao bound, optimal quantum resources states, and optimal detection strategies will need to be determined for each application. The theoretical community will need to play an active role to provide guidance as to the most promising unexplored areas when faced with novel functionality quantum sensors.

9.5 Milestones and deliverables WP-5 (years 1 / 3 / 5)

Milestones are underlined, deliverables are in *italic*.



Example 1: Recent theoretical investigations have shown that the detection of dark matter through its direct gravitational interaction is possible with a large array of opto-mechanical sensors that leverage quantum techniques such as squeezed light readout and back action evasion. An entangled network of opto-mechanical sensors can significantly alleviate the scaling requirement of the array.

Example 2: The scaling up of networked sensor arrays that can leverage quantum techniques for sensing will require new theoretical frameworks to establish the optimal quantum resource states, optimal measurement strategies, novel data analysis strategies, and fundamental sensitivity limits. Theoretical work that takes into account experimental imperfections will be needed to guide experimental work to fully levearge available quantum resources.

Over the last decade, innovative strategies employing non-classical measurement techniques have been shown to surpass the standard quantum limit of individual sensors. Networking such systems together opens up the possibility of further enhancements through collective measurements of multiple quantum-coherent sensors, as demonstrated by Ref. [142]. However, the optimal configuration and fundamental limits to collective measurements within networks of quantum-coherent sensors remain relatively unexplored, as does their application to searches of physics beyond the standard model.

10. WP 6 : CAPACITY BUILDING

Already while drafting the ECFA roadmap, two central themes (DRDT 5.3 and DRDT 5.4) emerged. These concerned the need to establish the necessary frameworks and mechanisms to allow exploration of emerging technologies (DRDT 5.3) and the need to develop and provide advanced enabling capabilities and infrastructure (DRDT 5.4). Building and enhancing the required capacities to effectively benefit from advances in the technological developments of WP-1 – WP-5 constitutes the core of this WP which partly overlaps with efforts in DRD9.

In many of the fields covered by DRD5 / RDq, developments in neighboring engineering and material science fields can open up significant new avenues. To enhance exchanges between quantum sensing efforts and these other fields, exchanges at several levels appear to hold promise and are, in some cases, essential in the medium term. These consist of:

- Information exchange platforms, where developers of novel materials and their potential users in particle physics can exchange ideas on needs and capabilities and share novel developments;
- Screening and characterization of materials and devices in a systematic / standardized manner (inter alia, testing samples with minimum ionizing radiation) via shared infrastructure and facilities;
- Developing a workforce familiar with the potential and challenges of quantum sensors, which requires building an educational and development platform

Before we address these three topics, we wish to first emphasize the importance of diversity, inclusion and equity, which is the backbone on which a successful educational program will be built.

work package	clocks & networks	super-conducting	kinetic sensors	atoms/ions/ molecules	opto-mechanical	nano-engineered / low-dimensional
WP-6a (Education)	X	X	X	X	X	X
WP-6b (Exchange platforms)	X	X	X	X	X	X
WP-6c (Test infrastructure)	X	X	X	X	X	X

Table 10. Quantum sensor families impacted by R&D in WP-6

Equity, Diversity and Inclusion

Quantum information science is a nascent area of research and provides a unique opportunity to make this research area fully equitable, diverse and inclusive. It is also important that at this early stage, the social impact of quantum science and technology is on the one side evaluated by researchers and on the other side understood by society. This DRD aims at integrating diversity, equity and inclusion as an intrinsic element towards advancing scientific excellence through quantum science research and at creating a research environment in which all members of the team feel they belong and can reach their full potential.

Diversity fosters creativity, empowers professional and personal growth and enriches the scientific community. The strategy of this DRD is to provide mentoring and professional development opportunities to everyone within the DRD. Every effort will be given to provide for a safe, and professional research and training environment to foster a sense of belonging among all members of the team. A key objective is to support training a new generation of experts in the field of quantum information science. As noted in section 10.1, this DRD intends to create a vigorous research-and-training program for students with targeted efforts to include underrepresented minority students. Mentorship will be provided to early-career members, with the goal of enabling their growth and pursue a successful career in science.

Another important goal is to create opportunities for underrepresented students across science, technology, engineering, and mathematics through internship programs. We will encourage the participating institutions to host interns for extended periods of time. These interns will work side-by-side with more senior scientists on research projects and participate in team meetings. All researchers will take a proactive role in mentoring the interns. This will not only provide for a meaningful research experience, but also help increase the representation of underrepresented groups and contribute to an overall more diverse and inclusive research community. The details of the internships will of course be decided by the host institution, but interns will be asked to deliver a summary of their work to the entire research team at the end of the internship, as a presentation and as a summary that will be shared with the DRD management. Feedback will be given by the full DRD team.

An important element in creating an inclusive environment is the ability to speak freely. Within RDq group members will take other people's ideas seriously and recognize that they might understand concepts and approach problems differently. Exclusion or derision of others based on different viewpoints will not be tolerated. All members are encouraged to share thoughts that could help improve any aspect of the operation of the collaboration. Micro-aggression, explicit, implicit, or unintended bias will be confronted. In group settings people's identities, culture and cultural norms, as well as language will be respected. Comments made with good intentions can still be hurtful. RDq will strive to be aware of how our words impact others.

10.1 WP-6a: Education platforms

Advancements in applications based on the quantum properties of systems require interdisciplinary approaches. Currently, most higher education institutions offer specialization in quantum technologies (QT) at the postgraduate level of Physics studies. However, the existing education schemes do not adequately prepare engineers and other specialists for the widespread adoption of QT in both frontier science and industry. Without a specialized workforce, the development of the field will be hindered unless appropriate measures are taken.

To address these challenges, the following three pillars are considered to be crucial:

- Upskilling existing professionals to increase multidisciplinarity
- Education based on microcredentials (see 10.1.2) instead of 4 year study plans
- Adapt the existing programs to ensure comparability of skills and of curricula

10.1.1 Quantum Sensing and Technology Schools

To create a focal point beyond the activities in the participating institutes, it makes sense to foresee longer-term common training opportunities with both lectures and hands-on laboratory activities. Prototyping such a combined curriculum could benefit from existing summer schools, such as at CERN, with large numbers of interested students.

After an initial trial and refining stage, the program could be cloned for implementation in initially a handful, and in the longer term a large number of existing summer or winter schools for students in particle physics. Such a program would allow standardized introductory lectures but also simple, low-cost laboratory equipment-based hands-on first experience with quantum sensors, their readout and their analysis. Establishing such a set of inexpensive but nevertheless relevant quantum technology kits / lab devices is one of the goals of this WP.

10.1.2 Education based on micro-credentials

Flexible education paths are becoming widely adopted in the academic community to provide specific training for a broader audience. The EU Council is recently introducing the micro-credentials[†] concept as a solution for specific domains of knowledge. Their flexible and lightweight structure, not confined to long-term study plans such as Bachelor's and Master's, allows higher education Institutions and Institutes to provide a high degree of specialization in continuously evolving fields, such as quantum sensing and quantum technologies. Another side effect of such structuring of studies is to go beyond the walls of a single institution. Several micro-credential courses can be followed instead of standard studies providing the student an opportunity to attend the courses given by leading institutions.

The first task will be to identify the individuals and institutions belonging to this Collaboration who are specialized in specific technology domains relevant to quantum sensing. After the initial stage, the implementation of educational programs based on micro-credentials will take place with trial courses in several institutions. After this first educational experience, the outcomes will be collected and refined towards a general distributed educational program shared by the participating institutions.

[†] Proposal for a COUNCIL RECOMMENDATION on a European approach to micro-credentials for lifelong learning and employability COM/2021/770 final
https://education.ec.europa.eu/education-levels/higher-education/micro-credentials

10.2 WP-6b: Exchange platforms

Due to the rapid advances in the many areas of Quantum Technologies worldwide, and the degree to which these require specialization, keeping abreast of developments in fields even somewhat removed from one's own area of specialization becomes increasingly challenging. Furthermore, communicating specific needs or interests in one area to researchers or developers in another one (e.g. the request to develop a nanodot with a specific emission wavelength or composition) relies mainly on existing personal networks. This WP attempts to develop an exchange platform that can connect experts in different fields, can match capabilities to potentially novel uses, and allows indicating interest in specific developments by some group to potential experts capable of carrying these out. De-facto, this is an attempt at growing a community interested in quantum sensing for particle physics around the quantum sensing R&D effort.

This to-be-created capacity / need exchange (or match-making) platform should be available preferentially to DRD5 / RDq collaborators but might also be of interest to industrial or commercial entitities.

10.3 WP-6c: Shared infrastructures

While overall, Quantum Sensing technologies require investments that lie below the scale of shared infrastructures typically required for High Energy Physics experiments, their costs (lasers, dilution refrigerators, exploratory device fabrication) remain at a level that deters smaller groups. At the same time, shared access to such existing medium-scale infrastructures can also be hampered by different interfaces, non-standardized platforms or administrative requirements.

This WP tackles these two challenges; intra-collaborator agreements to provide access to the dedicated specialized infrastructures held widely within the collaboration, together with the definition of a set of infrastructure-specific standardized interfaces (e.g. definition of the connection interface and of operational conditions for access to another group's dilution refrigerator) to allow different test set-ups to benefit from a facilitated access.

10.4 Milestones and deliverables WP-6 (years 1 / 3 / 5)

Milestones are underlined, deliverables are in *italic.*

WP-6a (Education)

WP6a →	μcredential structure →	QSensing School →	Student exchange
	List of Skills	*Syllabuses*	*Courses*

WP-6b (Exchange platforms)

WP6b →	platform structure →	platform implementation →	wide adoption
	structure description	*prototype database*	*full-fledged database*

WP-6c (Shared infrastructures)

WP6c →	prototype agreement →	first interface standards →	multiple standards
	interface document	*1^{st} IF implementation*	*multiple functional IF's*

Example 1: Bachelor-level Quantum Technology curriculum combining expertise from several universities with mutual recognition (in terms of credits) of courses provided in fields that are not locally available.

Example 2: Searchable database accessible to collaboration participants only that identifies a number of fields of expertise, with the additional functionalities of indicating interests, recent developments or opportunities, and possibly for providing relevant publications.

Example 3: List of minimal criteria and specific interface requirements for a non-local (but collaboration participating) group to be able to access infrastructure of a particular group (beam tests: logistical requirements; dilution refrigerator: connection interface, power limitations, vacuum requirements) but also listing potentially available resources (beam tests: beam telescope, DAQ, particle identification)

11. OVERVIEW OF DRD5 WORK PACKAGES

The proposed Work Packages are not all independent of each other; in fact, several WPs rely on progress made in other WPs or can enhance the effectiveness of work in them. Table 11 provides a rough indication of such cross-influences.

work package	WP1	WP2	WP3	WP4	WP5	WP6
WP 1 (Quantum systems in traps and beams)	-	(X)		(X)	X	X
WP 2 (Quantum materials: 0-, 1- and 2-D)	(X)	-		X		X
WP 3 (Superconducting quantum devices)	(X)	(X)	-	X		X
WP 4 (Scaled-up bulk systems)		X	X	-		X
WP 5 (Quantum techniques)	X	(X)	X	(X)	-	X
WP 6 (Capacity building)	X	X	X	X	X	-

Table 11. Work Package cross-influences and impacts. Developments in a given WP (left column) with a likely impact on another WP (top row) are indicated by 'X' (and by '(X)' if such an impact can be hypothesized but is not yet established).

11.1 Milestones and deliverables DRD5 / RD-q (years 1 / 3 / 5)

Tables 12, 13 and 14 summarize the milestones and deliverables of all the work packages of DRD5.

Work Package	Milestone / Deliverable	Due Date	Description
WP-1 Atomic, Nuclear, Molecular Systems and Nanoparticles in Traps and Beams			
a) Traps	M1a.1	2026	Advanced Trap technologies and quantum control for cooling and dressing
a) Traps	M1a.2	2026	Improved bound-state QED and nuclear structure theory calculations of exotic systems that may be used for Standard Model tests, including highly-charged ions and exotic atoms.
a) Traps	D1a.1	2027	Report of global analysis of exotic quantum trap systems
a) Traps	M1a.1	2027	UHV nanoparticle trap loading
b) Interferometry	M1b.1	2025	Formation of TVLBAI proto-collaboration
b) Interferometry	M1b.2	2028	Definition of instrumentation studies for roadmap
b) Interferometry	D1b.1	2029	Submission of TVLBAI roadmap
b) Interferometry	D1b.2	2027	Source flux of 10^{12} cold atoms at ≤ 2 μK
b) Interferometry	D1b.3	2027	Extended large momentum transfer techniques with number of pulses ≥ 1000.
b) Interferometry	D1b.4	2029	Quasi-continuous atom interferometry
b) Interferometry	M1b.3	2029	Squeezed atom interferometry with $\geq$ 20 dB squeezing
b) Interferometry	M1b.3	2029	Nanoparticle interference with mass $> 10^6$ amu
c) Clocks	M1c_a.1	2025	Design study for connecting specific institutes to the GÉANT C-TFN
c) Clocks	M1c_a.2	2027	Implement hardware for GÉANT C-TFN (freq. combs, cavity-stabilized lasers, freq. counters)
c) Clocks	M1c_a.3	2029	Establish cross-border links (e.g. C/L-band & C_1/C_2-channel)
c) Clocks	D1c_a.1	2025	Report for connecting to the GÉANT C-TFN
c) Clocks	D1c_a.2	2027	Establish network testbed for propagating best-performance time and frequency signals
c) Clocks	D1c_a.3	2029	Show best-performance with cross-border links
c) Clocks	M1c_b.1	2025	Parameter study of target parameters for portable clocks: freq stability, accuracy, reliability, etc.
c) Clocks	M1c_b.2	2027	Commission technology design study and hardware specifications (design study)
c) Clocks	M1c_b.3	2029	Identify and evaluate promising candidate clocks for portable use
c) Clocks	D1c_b.1	2025	Complete and deliver study of technical targets
c) Clocks	D1c_b.2	2027	Portable clock design study with hardware spec
c) Clocks	D1c_b.3	2029	Select most promising candidate clocks for portable use
WP-2 0,1,2-D and Quantum Materials			
a) Surveying and Tailoring	D2a.1	2025	Survey of existing quantum scintillators
a) Surveying and Tailoring	D2a.2	2026	Standardization of evaluation procedures
a) Surveying and Tailoring	D2a.3	2026	Standardization of evaluation of radiation hardness
a) Surveying and Tailoring	M2a.1	2027	Release of a database of quantum material properties
b) Community Building	M2b.1	2026	Workshop on engineered quantum materials for HEP
c) Simulation	M2c.1	2027	Integration and validation of quantum dots in Geant4
c) Simulation	D2c.1	2027	Development of extended, optimized Geant4 module for simulation of N-dimensional materials

Table 12. Deliverables and milestones for WP1 and WP2 as currently foreseen.

Work Package	Milestone / Deliverable	Due Date	Description
WP-3 Cryogenic materials, devices and systems			
a) 4K-stage	D3a.1	2026	Release of library of validated methodologies and devices at 4K
a) 4K-stage	D3a.2	2027	Availability of standardized setup for device testing at LHe temperatures
a) 4K-stage	M3a.1	2028	Availability of 4K ASIC in 28nm
b) Cryogenic Quantum Sensors	M3b.1	2026	Proposal for integration of high-T_C SNSPD detectors in beam experiment.
b) Cryogenic Quantum Sensors	M3b.2	2026	Establish a dedicated set of calibration lines in the hard x-ray and gamma-ray regime for TES and MMC.
b) Cryogenic Quantum Sensors	D3b.1	2027	Enhanced sensitivity of TES/KID-based light detectors
b) Cryogenic Quantum Sensors	D3b.2	2027	Development of TES/KID devices that operate below 50 mK
b) Cryogenic Quantum Sensors	D3b.3	2027	Development of chip-based microwave homodyne detectors
b) Cryogenic Quantum Sensors	D3b.4	2028	Full modeling and simulation of charged particle background
c) Resilient Integration	D3c.1	2028	Identification of high-priority technical challenges to integration
WP-4 Scaling Quantum			
a) Spin Polarized Ensembles	M4a.1	2026	Dedicated workshop & study to improve range of polarizable systems and techniques
a) Spin Polarized Ensembles	M4a.2	2028	Improved bulk polarizability and coherence times
a) Spin Polarized Ensembles	D4a.1	2027	Map of paths towards higher densities through improved techniques and expanded families
a) Spin Polarized Ensembles	D4a.2	2027	Implementation of multiple methods to increase coherence times and polarized fractions
b) Hybrid Devices	M4b.1	2025	Workshop bringing together different communities to explore integration of different technologies
b) Hybrid Devices	M4b.2	2027	Availability of engineered nanomaterial blocks for testing
b) Hybrid Devices	M4b.3	2029	Availability of engineered bulk nanomaterials for testing
b) Hybrid Devices	D4b.1	2026	Report on existing nanoscale opportunities and future device concepts
c) Opto-Mechanical Sensors	D4c.1	2027	Workshop focused on identifying particle physics targets for opto-mechanical systems beyond dark matter detection
c) Opto-Mechanical Sensors	M4c.1	2027	Establish theoretical sensitivity limits for different families of opto-mechanical sensors
c) Opto-Mechanical Sensors	M4c.2	2027	Achieving enhanced sensitivity of individual opto-mechanical sensors, through optimization of mass, Q-factor, readout method, etc., based on physics targets
c) Opto-Mechanical Sensors	M4c.3	2028	Develop quantum-coherent interconnects
c) Opto-Mechanical Sensors	M4c.4	2029	Demonstrate quantum advantage of a reduced sensing network

Table 13. Deliverables and milestones for WP3 –WP4 as currently foreseen.

Work Package	Milestone / Deliverable	Due Date	Description
WP-5 Quantum Techniques for Sensing			
a) Squeezing	M5a.1	2025	Determine fundamental theory limits for different platforms
a) Squeezing	M5a.2	2026	Determine platforms for which squeezing can lead to a quantum advantage
a) Squeezing	D5a.1	2026	Develop sources of squeezing with necessary wavelengths to interface with identified platforms
a) Squeezing	D5a.2	2027	Optimize squeezing sources to obtain 5 dB of squeezing
b) Entanglement	M5b.1	2026	Determine optimal entangled states, fundamental theory limits, and optimal detection configurations for a given system
b) Entanglement	D5b.1	2026	Develop scalable sources of multipartite entanglement
b) Entanglement	D5b.2	2027	Implement an array of sensors and determine classical limits to serve as benchmark
b) Entanglement	M5b.1	2028	Determine optimal readout for entangled sensor arrays
b) Entanglement	D5b.3	2029	Demonstrate quantum advantage of entanglement readout of a $\geq$5 sensor array
c) Backaction Evasion	M5c.1	2026	Determine theoretical framework for novel back action evasion strategies
c) Backaction Evasion	D5c.1	2027	Implement back action evasion strategies with a single sensor
c) Backaction Evasion	D5c.3	2028	Combine back action and squeezing for quantum enhancement over a broad bandwidth
c) Backaction Evasion	D5c.4	2029	Extend backaction to more than a single sensor
WP-6 Capacity Building			
a) Education Platforms	M6a.1	2026	Establish Quantum Sensing and Technology Summer School
a) Education Platforms	D6a.1	2026	Develop micro-credential-based quantum curriculum
b) Exchange Platform	D6a.2	2025	Hold first interdisciplinary quantum exchange workshop
c) Infrastructure	M6b.1	2027	Develop intra-collaborator agreements to share and expand existing infrastructure.

Table 14. Deliverables and milestones for WP5 – WP6 as currently foreseen.

12. ORGANIZATIONAL ASPECTS: COLLABORATION STRUCTURE, IP, INDUSTRIAL INVOLVEMENT

12.1 Collaborative issues and MOU

Standard CERN Collaboration agreements (memoranda of understanding, MOU's) will be used as a starting point in defining the structure of the DRD5 / RDq Collaboration, but with several significant simplifications. Among other,

- no annual membership fees or entrance fees will be raised for academic Collaborators;
- Collaborators can be individual university groups, other Collaborations, laboratories or other academic entities. The status of possible industrial partners will need to be clarified;
- acceptance of membership by an interested party is decided by the Collaboration Board, which is also to be informed in case a party wishes to leave the Collaboration

Given the expected large number of participating institutes and diversity in funding sources (funding agencies, universities, local funding and potentially industrial contributions) and the group characteristics, signing MOU's between CERN and every party appears daunting. Managing this effort requires on one hand a high-level MOU that defines the interaction between CERN as evaluation body and host (the DRDC) and the collaboration. In addition it will require very light-weight, standardized addenda to the MOU that detail each group's contributions that will be signed by a representative of the individual group, CERN's director of research, and the spokesperson of DRD5 / RDq. This approach is well matched to the spread in group size, administrative contexts of the groups, research foci, available group resources and geographic locations of the groups. It is thus expected that the six individual WP platforms will on one hand operate as autonomous discussion and exchange boards for the WP and sub-WP activities and should self-organize, and on the other hand should be in regular contact with the Management and Project Evaluation boards. Only in WP-6b is partitioning intentionally set aside, as the intention there is precisely to establish links across all the different quantum technologies of this collaboration's constituency.

12.2 Collaboration structure

The structure of this diverse and global Collaboration should be as lightweight as possible, while ensuring adequate representation of all involved entities. The model that is being considered is that of a **Coordinated Network amongst a wide range of heterogeneous groups interested in collaborating through information exchange and occasional shared developments**. Participation in the Collaboration ensures adhesion to a common set of goals, access to an interdisciplinary expert network, avoidance of excessive duplication of efforts, complementarity of approaches and participation in developments of particular interest to fundamental physics research.

With six quantum sensing families and six Work Packages (organized around six Working Groups or "platforms", each headed by the WP coordinator and whose membership consists of the corresponding WP and sub-WP coordinators), we envisage a collaboration structure (see Figure 3) in the form of:

- a **Management Board** (one spokesperson, one deputy spokesperson, and the chairs of the Collaboration board, the Resources board and the Project Oversight board); the spokesperson is the interface between the collaboration and the scientific committee (DRDC) on one hand, and represents the Collaboration publicly on the other hand.
- a **Collaboration Board** representing the collaborating institutes, with one representative per participating institute. The chair of this board is determined by election by the representatives.
- a **Project Oversight Board**, which is an elected structure consisting of experts from within the Collaboration. In addition to approximately three experts per quantum sensor family, each of the 6 Working Groups will be represented by their top-level WP coordinators. The role of the Project Oversight board is dual. On one hand, it oversees the developments of the different WPs as reported to it by the WP and sub-WP coordinators, and reports the overall progress to the MB. On the other hand, it has the expertise to evaluate any projects, submitted to it by teams of at least 3 collaborating groups, for scientific merit and against the overarching goals of the ECFA roadmap and the existing WPs. If a proposal falls outside the original WP's scope, the Project Oversight Board can provide letters of support to the proposing groups in the name of the overall DRD5 collaboration. Furthermore, liaison officers to the other DRD's will be selected from among the Project Oversight board's membership to ensure a good flow of information to and from the other DRD collaborations.
- Finally, we foresee a **Resources Review Board**, whose composition and membership rules are still under discussion, and whose role would be to provide an external viewpoint from among world experts in quantum sensing on the expenditures and sharing of costs of the Collaboration's R&D and on possible re-prioritizations.

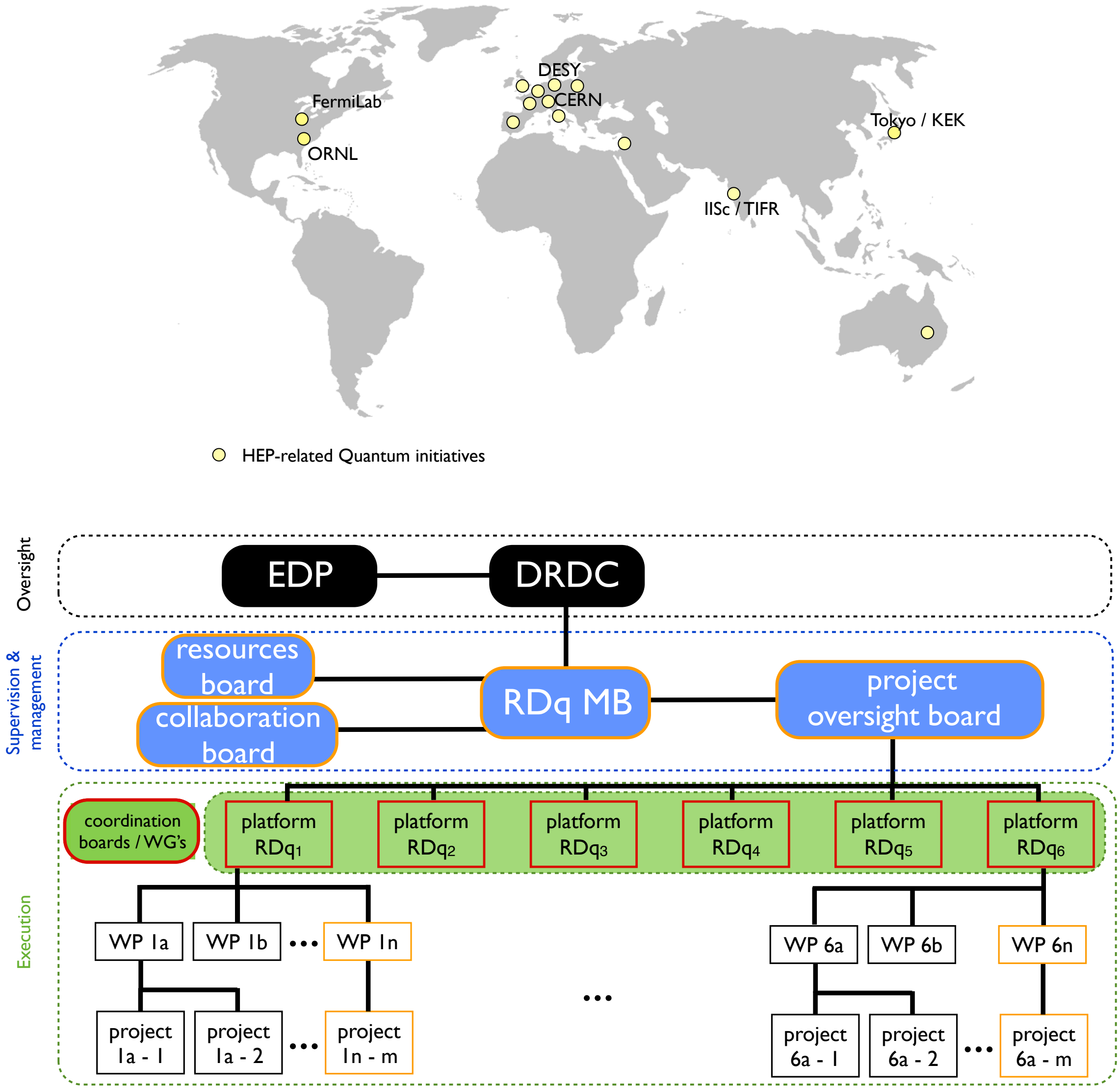
12.3 Issues related to the global scale of the proposal

Given the international scale of this collaboration and the administrative load of maintaining and coordinating wide-spread efforts, there is a need to have internationally distributed responsibilities. This will ease coordination of efforts related to the specific Work Packages world-wide, enable to provide progress reports to the Collaboration Board and the Management Board, and will facilitate shepherding additional activities related to the specific Work Packages and sub-WPs within and / or among the involved groups, but which might lie outside of the boundaries of the WP itself.

It is intended that each high-level WP ("platform") coordinator carries the responsibility for following both the overall WP as well as the set of WP-specific sub-WPs; the sub-WP coordinator's responsibility is limited to the specific sub-WP. As the groups involved in a specific sub-WP are themselves geographically spread out, this requires on one hand an equitable sharing of coordination responsibilities worldwide, and on the other hand, the willingness for all coordinators and groups participating in a specific sub-WP to interact with other groups and the sub-WP coordinator (which may well be based elsewhere) on a global scale. Naturally groups that are administratively tied to a specific WP coordinator can be involved in projects related to other WPs than those that their institution has a coordination and reporting responsibility for.

12.4 IP issues and industrial involvement

With the very rapid progress in the field of quantum sensing, industrial and commercial partners can be expected to be involved either as direct partners with specific collaborating institutes, or as interested participants. We do not foresee that such partners will become collaborators themselves, but do foresee a membership model in which such partners are informed of activities and progress on different detector R&D thrusts. Specific commercial /



(platforms may be mono-site or multi-site but carry the responsibility to shepherd the spread-out activities related to their specific WP)

Figure 3. Top: Geographic distribution of possible Work Package coordinators. Bottom: Collaboration organigram

industrial membership models may in turn be considered in light of their implications for addressing collaborative resource challenges.

At this point in time, the specific details of interaction with industrial/commercial partners are, however, not yet completely defined. Also not decided yet is their voice in potentially shaping some of the research directions. Issues such as patents, interaction with industry, licensing, sharing of IP (prior, created during collaboration, after a group leaves) will be defined in the initial phase of forming this Collaboration, with the baseline understanding that IP created by Collaborators belongs to them and their potential external partners (no common ownership), but that access to IP created in the context of the Collaboration shall remain available to the Collaboration members indefinitely, possibly against minimal licensing fees in case the Collaborator from whom the IP stems leaves the Collaboration. Given the worldwide interest and sensitivities in this field, the numerous actors involved, and the very active presence of, and collaboration with, industrial partners, a model relying on open IP is not appropriate to this Collaboration.

13. CONTRIBUTORS AND SIGNATORIES

13.1 Contributors and Conveners (alphabetic ordering)

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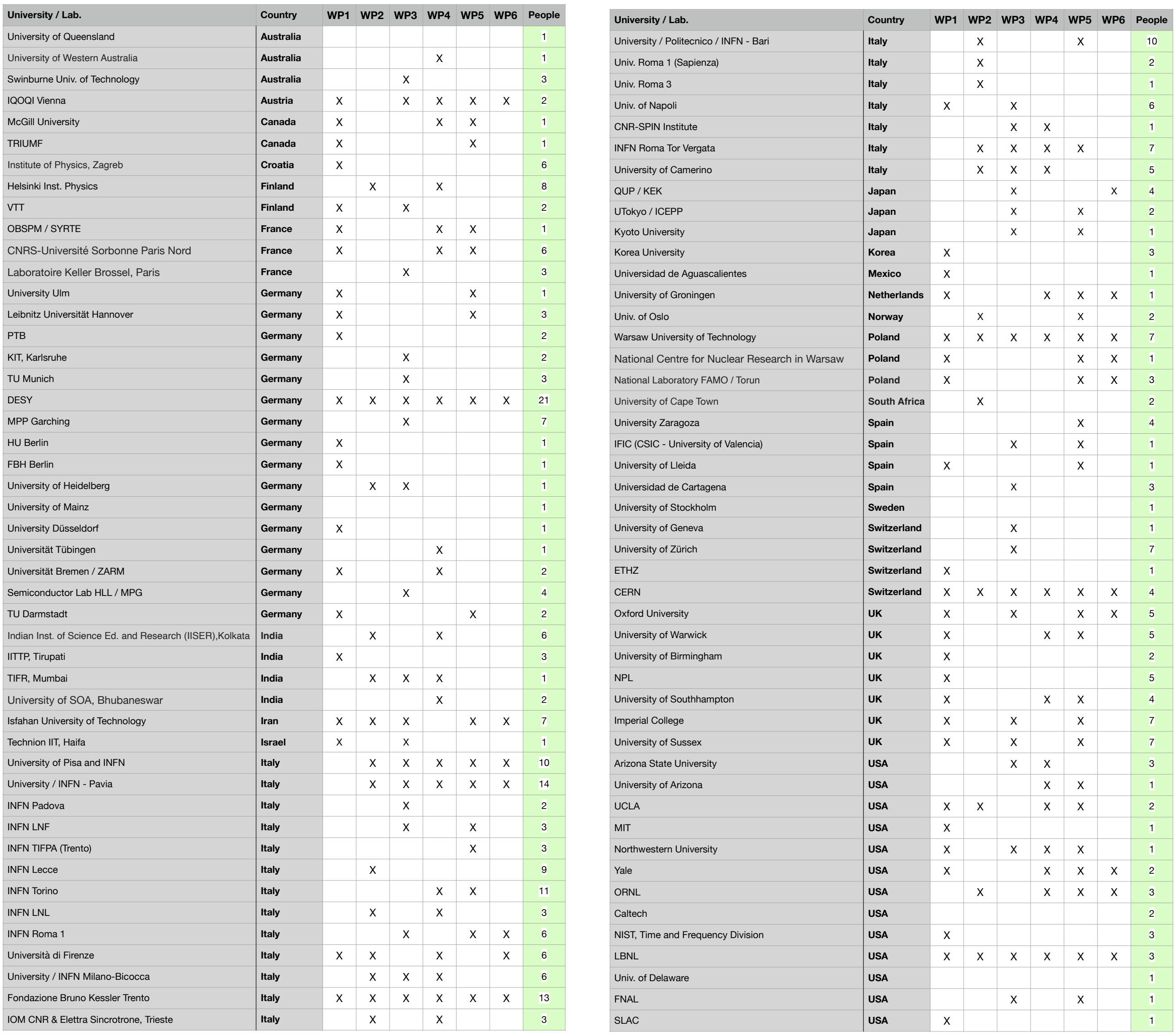
13.2 Signatories

In the following, the list of signatories to the present document is provided, in form of their institutional affiliation, with the understanding that this expression of interest by the signatories in no way implies any formal responsibility or commitment by their institutes nor their funding agencies. This list must in any case be considered dynamic, given the very tight deadlines available, and can be expected to evolve. A complete and up-to-date list will be provided upon request.

Figure 4 summarizes the expressed interests as of 22.3.2024 to be involved in specific WP's by individual groups from the listed institutes (in parentheses, the WP's they intend to be involved in). This list of Signatories (ordered alphabetically by country) is by no means exhaustive and will evolve over time.



University / Lab.	Country	WP1	WP2	WP3	WP4	WP5	WP6	People
University of Queensland	**Australia**							1
University of Western Australia	**Australia**				X			1
Swinburne Univ. of Technology	**Australia**			X				3
IQOQI Vienna	**Austria**	X		X	X	X	X	2
McGill University	**Canada**	X			X	X		1
TRIUMF	**Canada**	X				X		1
Institute of Physics, Zagreb	**Croatia**	X						6
Helsinki Inst. Physics	**Finland**		X		X			8
VTT	**Finland**	X		X				2
OBSPM / SYRTE	**France**	X			X	X		1
CNRS-Université Sorbonne Paris Nord	**France**	X			X	X		6
Laboratoire Keller Brossel, Paris	**France**			X				3
University Ulm	**Germany**	X				X		1
Leibnitz Universität Hannover	**Germany**	X				X		3
PTB	**Germany**	X						2
KIT, Karlsruhe	**Germany**			X				2
TU Munich	**Germany**			X				3
DESY	**Germany**	X	X	X	X	X	X	21
MPP Garching	**Germany**			X				7
HU Berlin	**Germany**	X						1
FBH Berlin	**Germany**	X						1
University of Heidelberg	**Germany**		X	X				1
University of Mainz	**Germany**							1
University Düsseldorf	**Germany**	X						1
Universität Tübingen	**Germany**				X			1
Universität Bremen / ZARM	**Germany**	X			X			2
Semiconductor Lab HLL / MPG	**Germany**			X				4
TU Darmstadt	**Germany**	X				X		2
Indian Inst. of Science Ed. and Research (IISER),Kolkata	**India**		X		X			6
IITTP, Tirupati	**India**	X						3
TIFR, Mumbai	**India**		X	X	X			1
University of SOA, Bhubaneswar	**India**				X			2
Isfahan University of Technology	**Iran**	X	X	X		X	X	7
Technion IIT, Haifa	**Israel**	X		X				1
University of Pisa and INFN	**Italy**		X	X	X	X	X	10
University / INFN - Pavia	**Italy**		X	X	X	X	X	14
INFN Padova	**Italy**			X				2
INFN LNF	**Italy**			X		X		3
INFN TIFPA (Trento)	**Italy**					X		3
INFN Lecce	**Italy**		X					9
INFN Torino	**Italy**				X	X		11
INFN LNL	**Italy**		X		X			3
INFN Roma 1	**Italy**			X		X	X	6
Università di Firenze	**Italy**	X	X		X		X	6
University / INFN Milano-Bicocca	**Italy**		X	X	X			6
Fondazione Bruno Kessler Trento	**Italy**	X	X	X	X	X	X	13
IOM CNR & Elettra Sincrotrone, Trieste	**Italy**		X		X			3
University / Politecnico / INFN - Bari	**Italy**		X			X		10
Univ. Roma 1 (Sapienza)	**Italy**		X					2
Univ. Roma 3	**Italy**		X					1
Univ. of Napoli	**Italy**	X		X				6
CNR-SPIN Institute	**Italy**			X	X			1
INFN Roma Tor Vergata	**Italy**		X	X	X	X		7
University of Camerino	**Italy**		X	X	X			5
QUP / KEK	**Japan**			X			X	4
UTokyo / ICEPP	**Japan**			X		X		2
Kyoto University	**Japan**			X		X		1
Korea University	**Korea**	X						3
Universidad de Aguascalientes	**Mexico**	X						1
University of Groningen	**Netherlands**	X			X	X	X	1
Univ. of Oslo	**Norway**		X			X		2
Warsaw University of Technology	**Poland**	X	X	X	X	X	X	7
National Centre for Nuclear Research in Warsaw	**Poland**	X				X	X	1
National Laboratory FAMO / Torun	**Poland**	X				X	X	3
University of Cape Town	**South Africa**		X					2
University Zaragoza	**Spain**					X		4
IFIC (CSIC - University of Valencia)	**Spain**			X		X		1
University of Lleida	**Spain**	X				X		1
Universidad de Cartagena	**Spain**			X				3
University of Stockholm	**Sweden**							1
University of Geneva	**Switzerland**			X				1
University of Zürich	**Switzerland**			X				7
ETHZ	**Switzerland**	X						1
CERN	**Switzerland**	X	X	X	X	X	X	4
Oxford University	**UK**	X		X		X	X	5
University of Warwick	**UK**	X			X	X		5
University of Birmingham	**UK**	X						2
NPL	**UK**	X						5
University of Southhampton	**UK**	X			X	X		4
Imperial College	**UK**	X		X		X		7
University of Sussex	**UK**	X		X		X		7
Arizona State University	**USA**			X	X			3
University of Arizona	**USA**				X	X		1
UCLA	**USA**	X	X		X	X		2
MIT	**USA**	X						1
Northwestern University	**USA**	X		X	X	X		1
Yale	**USA**	X			X	X	X	2
ORNL	**USA**		X		X	X	X	3
Caltech	**USA**							2
NIST, Time and Frequency Division	**USA**	X						3
LBNL	**USA**	X	X	X	X	X	X	3
Univ. of Delaware	**USA**							1
FNAL	**USA**			X		X		1
SLAC	**USA**	X						1

Figure 4. Mapping of institutes to Work Packages (signatories to the present proposal; any particular institute may regroup several separate groups active in different areas). Status as of 16.5.2024. The total number of institutes is 94 (although in some cases, several distinct groups within one institute may contribute to different WP's), the total number of involved individuals is 338. Assuming an average contribution of 30% per involved individual, WP's 1-6 regroup (21, 16, 18, 19, 18 and 9) FTE's each, spread over a number of institutes.

13.3 Resources and responsibilities

The responsibilities and resources for the targeted WP's are distributed on a global scale. In the initial phase of forming the collaboration, it is very difficult to provide a coherent overview of available resources and manpower, of resources required to achieve milestones that go beyond organizational and reporting, and expected contributions to common activities. Achieving such an overview will constitute one of the initial tasks of the collaboration board.

References

[1] ECFA Detector R&D Roadmap Process Group, "The 2021 ECFA detector research and development roadmap." https://cds.cern.ch/record/2784893/, 2021.

[2] M. Safronova, D. Budker, D. DeMille, D. F. J. Kimball, A. Derevianko, and C. W. Clark, "Search for new physics with atoms and molecules," Reviews of Modern Physics **90**, jun 2018.

[3] G. Cronenberg et al., "Acoustic Rabi oscillations between gravitational quantum states and impact on symmetron dark energy," Nature Physics **14**, p. 1022–1026, 2018.

[4] N. R. Hutzler, "Polyatomic molecules as quantum sensors for fundamental physics," Quantum Science and Technology **5**, p. 044011, 2020.

[5] T. Chupp and M. Ramsey-Musolf, "Electric dipole moments: A global analysis," Phys.Rev. C **91**, p. 035502, 2015.

[6] D. Carney, G. Krnjaic, D. C. Moore, C. A. Regal, et al., "Mechanical Quantum Sensing in the Search for Dark Matter," Quantum Sci. Technol. **6**, p. 024002, 2021.

[7] F. Monteiro, G. Afek, D. Carney, G. Krnjaic, J. Wang, and D. C. Moore, "Search for composite dark matter with optically levitated sensors," Phys. Rev. Lett. **125**(18), p. 181102, 2020.

[8] P. W. Graham, D. E. Kaplan, J. Mardon, S. Rajendran, and W. A. Terrano, "Dark matter direct detection with accelerometers," Phys. Rev. D **93**, p. 075029, Apr 2016.

[9] A. Arvanitaki and A. A. Geraci, "Detecting high-frequency gravitational waves with optically levitated sensors," Phys. Rev. Lett. **110**, p. 071105, Feb 2013.

[10] N. Aggarwal, G. P. Winstone, M. Teo, M. Baryakhtar, S. L. Larson, V. Kalogera, and A. A. Geraci, "Searching for new physics with a levitated-sensor-based gravitational-wave detector," Phys. Rev. Lett. **128**, p. 111101, Mar 2022.

[11] S. Bose, A. Mazumdar, G. W. Morley, H. Ulbricht, M. Toroš, M. Paternostro, A. A. Geraci, P. F. Barker, M. S. Kim, and G. Milburn, "Spin entanglement witness for quantum gravity," Phys. Rev. Lett. **119**, p. 240401, Dec 2017.

[12] C. Marletto and V. Vedral, "Gravitationally induced entanglement between two massive particles is sufficient evidence of quantum effects in gravity," Phys. Rev. Lett. **119**, p. 240402, Dec 2017.

[13] D. Carney, P. C. E. Stamp, and J. M. Taylor, "Tabletop experiments for quantum gravity: a user's manual," Classical and Quantum Gravity **36**(3), p. 034001, 2019.

[14] R. J. Marshman, A. Mazumdar, and S. Bose, "Locality and entanglement in table-top testing of the quantum nature of linearized gravity," Phys. Rev. A **101**(5), p. 052110, 2020.

[15] S. Bose, A. Mazumdar, M. Schut, and M. Toroš, "Mechanism for the quantum natured gravitons to entangle masses," Phys. Rev. D **105**(10), p. 106028, 2022.

[16] A. A. Geraci, S. B. Papp, and J. Kitching, "Short-range force detection using optically cooled levitated microspheres," Phys. Rev. Lett. **105**, p. 101101, Aug 2010.

[17] D. C. Moore and A. A. Geraci, "Searching for new physics using optically levitated sensors," Quantum Science and Technology **6**, p. 014008, jan 2021.

[18] P. F. Barker, S. Bose, R. J. Marshman, and A. Mazumdar, "Entanglement based tomography to probe new macroscopic forces," Phys. Rev. D **106**(4), p. L041901, 2022.

[19] S. Bose, A. Mazumdar, M. Schut, and M. Toroš, "Entanglement Witness for the Weak Equivalence Principle," Entropy **25**(3), p. 448, 2023.

[20] R. J. Marshman, A. Mazumdar, G. W. Morley, P. F. Barker, S. Hoekstra, and S. Bose, "Mesoscopic Interference for Metric and Curvature (MIMAC) & Gravitational Wave Detection," New J. Phys. **22**(8), p. 083012, 2020.

[21] D. C. Moore, A. D. Rider, and G. Gratta, "Search for millicharged particles using optically levitated microspheres," Phys. Rev. Lett. **113**, p. 251801, Dec 2014.

[22] S. Udrescu, S. Wilkins, A. Breier, et al., "Precision spectroscopy and laser-cooling scheme of a radium-containing molecule," Nat. Phys. **20**, p. 202–207, 2024.

[23] E. Tiesinga, P. J. Mohr, D. B. Newell, and B. N. Taylor, "CODATA recommended values of the fundamental physical constants: 2018," Rev. Mod. Phys. **93**, p. 025010, Jun 2021.

[24] S. G. Karshenboim, "Precision physics of simple atoms: QED tests, nuclear structure and fundamental constants," Physics Reports **422**(1), pp. 1–63, 2005.

[25] S. G. Karshenboim and V. G. Ivanov, Quantum Electrodynamics, High-Resolution Spectroscopy and Fundamental Constants, pp. 237–265. Springer International Publishing, Cham, 2018.

[26] S. G. Karshenboim, "Precision physics of simple atoms and constraints on a light boson with ultraweak coupling," Phys. Rev. Lett. **104**, p. 220406, Jun 2010.

[27] S. G. Karshenboim and V. V. Flambaum, "Constraint on axionlike particles from atomic physics," Phys. Rev. A **84**, p. 064502, Dec 2011.

[28] E. J. Salumbides, J. C. J. Koelemeij, J. Komasa, K. Pachucki, K. S. E. Eikema, and W. Ubachs, "Bounds on fifth forces from precision measurements on molecules," Phys. Rev. D **87**, p. 112008, Jun 2013.

[29] C. Delaunay, C. Frugiuele, E. Fuchs, and Y. Soreq, "Probing new spin-independent interactions through precision spectroscopy in atoms with few electrons," Phys. Rev. D **96**(11), p. 115002, 2017.

[30] M. I. Eides, "Hyperfine splitting in muonium: Accuracy of the theoretical prediction," Physics Letters B **795**, pp. 113–116, 2019.

[31] S. G. Karshenboim, A. Ozawa, V. A. Shelyuto, E. Y. Korzinin, R. Szafron, and V. G. Ivanov, "The complete $\alpha 8$ m contributions to the 1 s lamb shift in hydrogen," Physics of Particles and Nuclei **53**(4), pp. 773–786, 2022.

[32] K. Pachucki, V. c. v. Patkóš, and V. A. Yerokhin, "Three-photon-exchange nuclear structure correction in hydrogenic systems," Phys. Rev. A **97**, p. 062511, Jun 2018.

[33] G. Janka, B. Ohayon, and P. Crivelli, "Muonium lamb shift: theory update and experimental prospects," in EPJ Web of Conferences, **262**, p. 01001, EDP Sciences, 2022.

[34] I. Cortinovis, B. Ohayon, L. de Sousa Borges, G. Janka, A. Golovizin, N. Zhadnov, and P. Crivelli, "Update of Muonium 1 S–2 S transition frequency," The European Physical Journal D **77**(4), p. 66, 2023.

[35] P. Strasser, M. Abe, M. Aoki, S. Choi, Y. Fukao, Y. Higashi, T. Higuchi, H. Iinuma, Y. Ikedo, K. Ishida, et al., "New precise measurements of muonium hyperfine structure at J-PARC MUSE," in EPJ Web of Conferences, **198**, p. 00003, EDP Sciences, 2019.

[36] C. Delaunay, B. Ohayon, and Y. Soreq, "Towards an independent determination of muon $g-2$ from muonium spectroscopy," Phys. Rev. Lett. **127**, p. 251801, Dec 2021.

[37] D. P. Aguillard et al., "Measurement of the Positive Muon Anomalous Magnetic Moment to 0.20 ppm," Phys. Rev. Lett. **131**(16), p. 161802, 2023.

[38] D. A. Glazov, F. Köhler-Langes, A. V. Volotka, K. Blaum, F. Heiße, G. Plunien, W. Quint, S. Rau, V. M. Shabaev, S. Sturm, and G. Werth, "g Factor of Lithiumlike Silicon: New Challenge to Bound-State QED," Phys. Rev. Lett. **123**, p. 173001, Oct 2019.

[39] T. Sailer, V. Debierre, Z. Harman, F. Heiße, C. König, J. Morgner, B. Tu, A. V. Volotka, C. H. Keitel, K. Blaum, et al., "Measurement of the bound-electron g-factor difference in coupled ions," Nature **606**(7914), pp. 479–483, 2022.

[40] Morgner, J and Tu, B and König, CM and Sailer, T and Heiße, F and Bekker, H and Sikora, B and Lyu, C and Yerokhin, VA and Harman, Z and others, "Stringent test of QED with hydrogen-like tin," Nature **622**(7981), pp. 53–57, 2023.

[41] V. I. Korobov and J.-P. Karr, "Spin–orbit interaction in the HD+ ion," The European Physical Journal D **76**(10), p. 197, 2022.

[42] S. Alighanbari, I. V. Kortunov, G. S. Giri, and S. Schiller, "Test of charged baryon interaction with high-resolution vibrational spectroscopy of molecular hydrogen ions," Nature Physics **19**(9), pp. 1263–1269,

2023.

[43] K. Pachucki, V. c. v. Patkóš, and V. A. Yerokhin, "Testing fundamental interactions on the helium atom," Phys. Rev. A **95**, p. 062510, Jun 2017.

[44] V. A. Yerokhin, V. Patkóš, and K. Pachucki, "Atomic structure calculations of helium with correlated exponential functions," Symmetry **13**(7), 2021.

[45] G. Clausen, S. Scheidegger, J. A. Agner, H. Schmutz, and F. Merkt, "Imaging-Assisted Single-Photon Doppler-Free Laser Spectroscopy and the Ionization Energy of Metastable Triplet Helium," Phys. Rev. Lett. **131**, p. 103001, Sep 2023.

[46] K. Pachucki and V. A. Yerokhin, "Fine structure of heliumlike ions and determination of the fine structure constant," Phys. Rev. Lett. **104**, p. 070403, Feb 2010.

[47] V. A. Yerokhin, V. c. v. Patkóš, and K. Pachucki, "QED $m\alpha^7$ effects for triplet states of heliumlike ions," Phys. Rev. A **107**, p. 012810, Jan 2023.

[48] Aßmann, T., and Giese, E. and Di Pumpo, F., "Quantum field theory for multipolar composite bosons with mass defect and relativistic corrections,"

[49] K. Pachucki, V. c. v. Patkóš, and V. A. Yerokhin, "Three-photon-exchange nuclear structure correction in hydrogenic systems," Phys. Rev. A **97**, p. 062511, Jun 2018.

[50] K. Pachucki, "Nuclear recoil correction to the hyperfine splitting in atomic systems," Phys. Rev. A **106**, p. 022802, Aug 2022.

[51] K. Pachucki and V. A. Yerokhin, "QED Theory of the Nuclear Recoil with Finite Size," Phys. Rev. Lett. **130**, p. 053002, Feb 2023.

[52] A. Antognini, S. Bacca, A. Fleischmann, L. Gastaldo, F. Hagelstein, P. Indelicato, A. Knecht, V. Lensky, B. Ohayon, V. Pascalutsa, et al., "Muonic-Atom Spectroscopy and Impact on Nuclear Structure and Precision QED Theory," arXiv preprint arXiv:2210.16929 , 10 2022.

[53] K. Pachucki, V. Lensky, F. Hagelstein, S. S. Li Muli, S. Bacca, and R. Pohl, "Comprehensive theory of the Lamb shift in light muonic atoms," 12 2022.

[54] M. Puchalski, J. Komasa, and K. Pachucki, "Hyperfine structure of the 2^3p state in ^{9}Be and the nuclear quadrupole moment," Phys. Rev. Res. **3**, p. 013293, Mar 2021.

[55] V. c. v. Patkóš, V. A. Yerokhin, and K. Pachucki, "Nuclear polarizability effects in ^{3}He$^+$ hyperfine splitting," Phys. Rev. A **107**, p. 052802, May 2023.

[56] J. Hur, D. P. L. Aude Craik, I. Counts, E. Knyazev, L. Caldwell, C. Leung, S. Pandey, J. C. Berengut, A. Geddes, W. Nazarewicz, P.-G. Reinhard, A. Kawasaki, H. Jeon, W. Jhe, and V. Vuletić, "Evidence of two-source king plot nonlinearity in spectroscopic search for new boson," Phys. Rev. Lett. **128**, p. 163201, Apr 2022.

[57] C. Delaunay, J.-P. Karr, T. Kitahara, J. C. J. Koelemeij, Y. Soreq, and J. Zupan, "Self-consistent extraction of spectroscopic bounds on light new physics," Phys. Rev. Lett. **130**, p. 121801, Mar 2023.

[58] Y. Margalit et al., "Realization of a complete Stern-Gerlach interferometer: Towards a test of quantum gravity," 11 2020.

[59] O. Buchmueller, J. Ellis, and U. Schneider, "Large-Scale Atom Interferometry for Fundamental Physics," arXiv preprint arXiv:2306.17726 , 6 2023.

[60] S. Abend et al., "Terrestrial Very-Long-Baseline Atom Interferometry: Workshop Summary," arXiv preprint arXiv:2310.08183 , 10 2023.

[61] T. Cecil, K. Irwin, R. Maruyama, M. Pyle, and S. Zorzetti, "Report of the topical group on quantum sensors for snowmass 2021," 2022.

[62] S. M. Dickerson, J. M. Hogan, A. Sugarbaker, D. M. S. Johnson, and M. A. Kasevich, "Multiaxis inertial sensing with long-time point source atom interferometry," Phys. Rev. Lett. **111**, p. 083001, 2013.

[63] M. Abe, P. Adamson, M. Borcean, D. Bortoletto, K. Bridges, et al., "Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100)," Quantum Science and Technology **6**, p. 044003, July 2021.

[64] B. Canuel, A. Bertoldi, L. Amand, E. Pozzo di Borgo, T. Chantrait, et al., "Exploring gravity with the MIGA large scale atom interferometer," Scientific Reports **8**, Sept. 2018.

[65] D. Schlippert, C. Meiners, R. Rengelink, C. Schubert, D. Tell, et al., "Matter-wave interferometry for inertial sensing and tests of fundamental physics," in Proceedings of the Eighth Meeting on CPT and Lorentz Symmetry, pp. 37–40, World Scientific, 2020.

[66] L. Badurina et al., "AION: An Atom Interferometer Observatory and Network," JCAP **05**, p. 011, 2020.

[67] B. Canuel, S. Abend, P. Amaro-Seoane, F. Badaracco, Q. Beaufils, et al., "Technologies for the ELGAR large scale atom interferometer array," 2020.

[68] B. Canuel, S. Abend, P. Amaro-Seoane, F. Badaracco, Q. Beaufils, et al., "ELGAR—a european laboratory for gravitation and atom-interferometric research," Classical and Quantum Gravity **37**, p. 225017, oct 2020.

[69] M.-S. Zhan, J. Wang, W.-T. Ni, D.-F. Gao, G. Wang, et al., "ZAIGA: Zhaoshan long-baseline atom interferometer gravitation antenna," International Journal of Modern Physics D **29**, p. 1940005, July 2019.

[70] Y. A. El-Neaj, C. Alpigiani, S. Amairi-Pyka, H. Araújo, A. Balaž, et al., "AEDGE: Atomic Experiment for Dark matter and Gravity Exploration in space," EPJ Quantum Technol. **7**, p. 127, 2020.

[71] CERN, "Terrestrial Very-Long-Baseline Atom Interferometry Workshop." `https://indico.cern.ch/event/1208783/`.

[72] F. Di Pumpo, A. Friedrich, and E. Giese, "Optimal baseline exploitation in vertical dark-matter detectors based on atom interferometry," AVS Quantum Science **6**, p. 014404, 01 2024.

[73] A. D. Ludlow, M. M. Boyd, J. Ye, E. Peik, and P. O. Schmidt, "Optical atomic clocks," Reviews of Modern Physics **87**(2), p. 637, 2015.

[74] F. Riehle, "Optical clock networks," Nature Photonics **11**(1), pp. 25–31, 2017.

[75] N. Sherrill, A. O. Parsons, C. F. A. Baynham, W. Bowden, E. A. Curtis, et al., "Analysis of atomic-clock data to constrain variations of fundamental constants," 2023.

[76] C. Sanner, N. Huntemann, R. Lange, C. Tamm, E. Peik, M. S. Safronova, and S. G. Porsev, "Optical clock comparison for lorentz symmetry testing," Nature **567**(7747), pp. 204–208, 2019.

[77] T. Bothwell, C. J. Kennedy, A. Aeppli, D. Kedar, J. M. Robinson, E. Oelker, A. Staron, and J. Ye, "Resolving the gravitational redshift across a millimetre-scale atomic sample," Nature **602**, p. 420–424, Feb. 2022.

[78] M. Filzinger, S. Dörscher, R. Lange, J. Klose, M. Steinel, E. Benkler, E. Peik, C. Lisdat, and N. Huntemann, "Improved limits on the coupling of ultralight bosonic dark matter to photons from optical atomic clock comparisons," Phys. Rev. Lett. **130**, p. 253001, Jun 2023.

[79] P. Wcisło, P. Ablewski, K. Beloy, S. Bilicki, M. Bober, et al., "New bounds on dark matter coupling from a global network of optical atomic clocks," Science advances **4**, p. eaau4869, December 2018.

[80] B. M. Roberts, P. Delva, A. Al-Masoudi, A. Amy-Klein, C. Bærentsen, et al., "Search for transient variations of the fine structure constant and dark matter using fiber-linked optical atomic clocks," New Journal of Physics **22**, p. 093010, sep 2020.

[81] G. Barontini, L. Blackburn, V. Boyer, F. Butuc-Mayer, X. Calmet, et al., "Measuring the stability of fundamental constants with a network of clocks," EPJ Quantum Technology **9**, May 2022.

[82] CLONETS Consortium, "Clock network services design study (CLONETS-DS)." `https://clonets.eu`, `https://clonets-ds.eu/?page_id=98`, 2022.

[83] GEANT Organisation, "GÈant core time frequency network (C-TFN)." `https://geant.org`, `https://wiki.geant.org/display/NETDEV/OTFN`, 2023.

[84] E. D. Caldwell, J.-D. Deschenes, J. Ellis, W. C. Swann, B. K. Stuhl, H. Bergeron, N. R. Newbury, and L. C. Sinclair, "Quantum-limited optical time transfer for future geosynchronous links," Nature **618**(7966), pp. 721–726, 2023.

[85] K. Beloy, M. I. Bodine, T. Bothwell, S. M. Brewer, Bromley, Sarah L. et al., and Boulder Atomic Clock Optical Network (BACON) Collaboration*, "Frequency ratio measurements at 18-digit accuracy using an optical clock network," Nature **591**(7851), pp. 564–569, 2021.

[86] L. Bonenberg, B. Motella, and J. Fortuny Guasch, "Assessing alternative positioning, navigation and timing technologies for potential deployment in the EU," Scientific analysis or review KJ-NA-31-450-EN-N (online), European Union, Luxembourg (Luxembourg), 2023.

[87] M. Delehaye and C. Lacroûte, "Single-ion, transportable optical atomic clocks," Journal of Modern Optics **65**(5-6), pp. 622–639, 2018.

[88] M. Takamoto, Y. Tanaka, and H. Katori, "A perspective on the future of transportable optical lattice clocks," Applied Physics Letters **120**(14), pp. 140502–1–140502–8, 2022.

[89] J. Cassidy and M. Zamkov, "Nanoshell quantum dots: Quantum confinement beyond the exciton Bohr radius," The Journal of Chemical Physics **152**, p. 110902, mar 2020.

[90] Q. Chen, J. Wu, X. Ou, B. Huang, J. Almutlaq, et al., “All-inorganic perovskite nanocrystal scintillators,” Nature **561**, pp. 88–93, sep 2018.

[91] M. Gandini, I. Villa, M. Beretta, C. Gotti, M. Imran, et al., “Efficient, fast and reabsorption-free perovskite nanocrystal-based sensitized plastic scintillators,” Nature Nanotechnology **15**, pp. 462–468, jun 2020.

[92] Z. Meng, B. Mahler, J. Houel, F. Kulzer, G. Ledoux, A. Vasil’ev, and C. Dujardin, “Perspectives for CdSe/CdS spherical quantum wells as rapid-response nano-scintillators,” Nanoscale **13**(46), pp. 19578–19586, 2021.

[93] L. A. Padilha, W. K. Bae, V. I. Klimov, J. M. Pietryga, and R. D. Schaller, “Response of Semiconductor Nanocrystals to Extremely Energetic Excitation,” Nano Letters **13**, pp. 925–932, mar 2013.

[94] T. Hubáček, A. Hospodková, K. Kuldová, J. Oswald, J. Pangrác, V. Jarỳ, F. Dominec, M. S. Zíková, F. Hájek, E. Hulicius, et al., “Advancement toward ultra-thick and bright InGaN/GaN structures with a high number of qws,” CrystEngComm **21**(2), pp. 356–362, 2019.

[95] L. Procházková, V. Čuba, J. Mrazek, A. Beitlerova, V. Jarỳ, and M. Nikl, “Preparation of Zn (Cd) O: Ga–SiO2 Composite Scintillating Materials,” Radiation Measurements **90**, pp. 59–63, 2016.

[96] A. Erroi, S. Mecca, M. L. Zaffalon, I. Frank, F. Carulli, A. Cemmi, I. Di Sarcina, D. Debellis, F. Rossi, F. Cova, et al., “Ultrafast and radiation-hard lead halide perovskite nanocomposite scintillators,” ACS Energy Letters **8**(9), pp. 3883–3894, 2023.

[97] K. Děcká, F. Pagano, I. Frank, N. Kratochwil, E. Mihóková, E. Auffray, and V. Čuba, “Timing performance of lead halide perovskite nanoscintillators embedded in a polystyrene matrix,” Journal of Materials Chemistry C **10**(35), pp. 12836–12843, 2022.

[98] C. Roques-Carmes, N. Rivera, A. Ghorashi, S. E. Kooi, et al., “A framework for scintillation in nanophotonics,” Science **375**, Feb 2022.

[99] S. Agostinelli et al., “GEANT4–a simulation toolkit,” Nucl. Instrum. Meth. A **506**, pp. 250–303, 2003.

[100] S. Oktyabrsky, M. Yakimov, V. Tokranov, and P. Murat, “Integrated semiconductor quantum dot scintillation detector: Ultimate limit for speed and light yield,” IEEE Transactions on Nuclear Science **63**(2), pp. 656–663, 2016.

[101] AIDAinnova, “Paving the way for a new generation of fine-sampling calorimeters using nanocomposite scintillating materials.” https://aidainnova.web.cern.ch/paving-way-new-generation-fine-sampling-calorimeters-using-nanocomposite-scintillating-materials 2024. Accessed: 2024-01-29.

[102] A. Datta, B. Barman, S. Magill, and S. Motakef, “Highly efficient photon detection systems for noble liquid detectors based on perovskite quantum dots,” Sci. Rep. **10**(1), p. 16932, 2020.

[103] S. Cherednichenko, N. Acharya, E. Novoselov, and V. Drakinskiy, “Low kinetic inductance superconducting mgb2 nanowires with a 130 ps relaxation time for single-photon detection applications,” Superconductor Science and Technology **34**, p. 044001, feb 2021.

[104] T. Polakovic, W. Armstrong, G. Karapetrov, Z.-E. Meziani, and V. Novosad, “Unconventional applications of superconducting nanowire single photon detectors,” Nanomaterials **10**(6), 2020.

[105] S. R. Golwala and E. Figueroa-Feliciano, “Novel quantum sensors for light dark matter and neutrino detection,” Annual Review of Nuclear and Particle Science **72**(1), pp. 419–446, 2022.

[106] C. Macklin et al., “A near quantum-limited josephson traveling-wave parametric amplifier,” Science **350**(6258), pp. 307–310, 2015.

[107] B. Ho Eom et al., “A wideband, low-noise superconducting amplifier with high dynamic range,” Nature Physics **8**, pp. 623–627, Aug 2012.

[108] M. Malnou et al., “Three-wave mixing kinetic inductance traveling-wave amplifier with near-quantum-limited noise performance,” PRX Quantum **2**, p. 010302, Jan 2021.

[109] M. Xu, R. Cheng, Y. Wu, G. Liu, and H. X. Tang, “Magnetic Field-Resilient Quantum-Limited Parametric Amplifier,” PRX Quantum **4**(1), p. 010322, 2023.

[110] M. Malnou et al., “Performance of a kinetic inductance traveling-wave parametric amplifier at 4 kelvin: Toward an alternative to semiconductor amplifiers,” Phys. Rev. Appl. **17**, p. 044009, Apr 2022.

[111] H. McCarrick et al., “The Simons Observatory Microwave SQUID Multiplexing Detector Module Design,” Astrophys. J. **922**(1), p. 38, 2021.

[112] B. Alpert et al., “High-resolution high-speed microwave-multiplexed low temperature microcalorimeters

for the HOLMES experiment," Eur. Phys. J. C **79**(4), p. 304, 2019.

[113] L. Gastaldo et al., "The electron capture in^{163}Ho experiment – ECHo," Eur. Phys. J. ST **226**(8), pp. 1623–1694, 2017.

[114] T. Okumura, T. Azuma, D. A. Bennett, I. Chiu, W. B. Doriese, et al., "Proof-of-principle experiment for testing strong-field quantum electrodynamics with exotic atoms: High precision x-ray spectroscopy of muonic neon," Phys. Rev. Lett. **130**, p. 173001, Apr 2023.

[115] HEATES Collaboration and S. Okada, D. A. Bennett, C. Curceanu, W. B. Doriese, et al., "First application of superconducting transition-edge sensor microcalorimeters to hadronic atom X-ray spectroscopy," Progress of Theoretical and Experimental Physics **2016**, p. 091D01, 09 2016.

[116] T. Hashimoto, D. A. Bennett, W. B. Doriese, M. S. Durkin, et al., "Integration of a TES-based X-ray spectrometer in a kaonic atom experiment," J. Low Temp. Phys. **199**, p. 1018, 2020.

[117] T. ISHIDA, "Superconducting neutron detectors and their application to imaging," IEICE Transactions on Electronics **E103.C**(5), pp. 198–203, 2020.

[118] M. H. Mendenhall, L. T. Hudson, C. I. Szabo, A. Henins, and J. P. Cline, "The molybdenum K-shell x-ray emission spectrum," J. Phys. B: At., Mol. Opt. Phys. **52**, p. 215004, 2019.

[119] J. Manley, M. D. Chowdhury, D. Grin, S. Singh, and D. J. Wilson, "Searching for vector dark matter with an optomechanical accelerometer," Phys. Rev. Lett. **126**(6), p. 061301, 2021.

[120] A. A. Geraci, C. Bradley, D. Gao, J. Weinstein, and A. Derevianko, "Searching for ultralight dark matter with optical cavities," Phys. Rev. Lett. **123**, p. 031304, Jul 2019.

[121] Y. Hochberg, I. Charaev, S.-W. Nam, V. Verma, M. Colangelo, and K. K. Berggren, "Detecting sub-gev dark matter with superconducting nanowires," Phys. Rev. Lett. **123**, p. 151802, Oct 2019.

[122] Y. Hochberg, Y. Kahn, M. Lisanti, C. G. Tully, and K. M. Zurek, "Directional detection of dark matter with two-dimensional targets," Physics Letters B **772**, pp. 239–246, 2017.

[123] G. Hallais, C. Renard, A. Barbier, E. Imbernon, and N. Fourches, "Pixel device based on a quantum well: Preliminary results on gate dielectrics," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **1047**, p. 167906, 2023.

[124] N. Crescini, C. Braggio, G. Carugno, P. Falferi, A. Ortolan, and G. Ruoso, "The QUAX-gpgs experiment to search for monopole-dipole Axion interaction," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **842**, pp. 109–113, 2017.

[125] A. Arvanitaki and A. A. Geraci, "Resonantly detecting axion-mediated forces with nuclear magnetic resonance," Phys. Rev. Lett. **113**, p. 161801, Oct 2014.

[126] W. P. Bowen and G. J. Milburn, Quantum optomechanics, CRC Press, 2015.

[127] M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt, "Cavity optomechanics," Rev. Mod. Phys. **86**, pp. 1391–1452, Dec 2014.

[128] G. Ranjit, M. Cunningham, K. Casey, and A. A. Geraci, "Zeptonewton force sensing with nanospheres in an optical lattice," Phys. Rev. A **93**, p. 053801, May 2016.

[129] D. Carney, G. Krnjaic, D. C. Moore, C. A. Regal, G. Afek, S. Bhave, B. Brubaker, T. Corbitt, J. Cripe, N. Crisosto, et al., "Mechanical quantum sensing in the search for dark matter," Quantum Science and Technology **6**(2), p. 024002, 2021.

[130] D. C. Moore and A. A. Geraci, "Searching for new physics using optically levitated sensors," Quantum Science and Technology **6**(1), p. 014008, 2021.

[131] D. Antypas, A. Banerjee, C. Bartram, M. Baryakhtar, J. Betz, J. Bollinger, C. Boutan, D. Bowring, D. Budker, D. Carney, et al., "New horizons: scalar and vector ultralight dark matter," arXiv preprint arXiv:2203.14915 , 2022.

[132] A. Arvanitaki, S. Dimopoulos, and K. Van Tilburg, "Sound of Dark Matter: Searching for Light Scalars with Resonant-Mass Detectors.," Phys. Rev. Lett. **116**, p. 031102, jan 2016.

[133] D. Carney, A. Hook, Z. Liu, J. M. Taylor, and Y. Zhao, "Ultralight dark matter detection with mechanical quantum sensors," New Journal of Physics **23**(2), p. 023041, 2021.

[134] J. Manley, D. J. Wilson, R. Stump, D. Grin, and S. Singh, "Searching for scalar dark matter with compact mechanical resonators," Physical review letters **124**(15), p. 151301, 2020.

[135] D. Carney, S. Ghosh, G. Krnjaic, and J. M. Taylor, "Proposal for gravitational direct detection of dark matter," Phys. Rev. D **102**, p. 072003, Oct 2020.

[136] D. Carney, K. G. Leach, and D. C. Moore, "Searches for massive neutrinos with mechanical quantum sensors," PRX Quantum **4**(1), p. 010315, 2023.

[137] S. Singh, L. De Lorenzo, I. Pikovski, and K. Schwab, "Detecting continuous gravitational waves with superfluid 4he," New Journal of Physics **19**(7), p. 073023, 2017.

[138] V. Vadakkumbatt, M. Hirschel, J. Manley, T. J. Clark, S. Singh, and J. P. Davis, "Prototype superfluid gravitational wave detector," Phys. Rev. D **104**, p. 082001, Oct 2021.

[139] A. Lo, P. Haslinger, E. Mizrachi, L. Anderegg, H. Müller, M. Hohensee, M. Goryachev, and M. E. Tobar, "Acoustic tests of lorentz symmetry using quartz oscillators," Phys. Rev. X **6**, p. 011018, Feb 2016.

[140] M. Hirschel, V. Vadakkumbatt, N. Baker, F. Schweizer, J. Sankey, S. Singh, and J. Davis, "Helios: The superfluid helium ultralight dark matter detector," arXiv preprint arXiv:2309.07995 , 2023.

[141] C. G. Baker, W. P. Bowen, P. Cox, M. J. Dolan, M. Goryachev, and G. Harris, "Optomechanical dark matter direct detection," arXiv preprint arXiv:2306.09726 , 2023.

[142] Y. Xia, A. R. Agrawal, C. M. Pluchar, A. J. Brady, Z. Liu, Q. Zhuang, D. J. Wilson, and Z. Zhang, "Entanglement-enhanced optomechanical sensing," Nature Photonics **17**(6), pp. 470–477, 2023.

[143] F. Spengler, D. Rätzel, and D. Braun, "Perspectives of measuring gravitational effects of laser light and particle beams," New Journal of Physics **24**, p. 053021, May 2022. Publisher: IOP Publishing.

[144] D. Braun and S. Popescu, "Coherently enhanced measurements in classical mechanics," Quantum Measurements and Quantum Metrology **2**, Aug. 2014.

[145] J. M. E. Fraïsse and D. Braun, "Coherent averaging," Annalen der Physik **527**, pp. 701–712, July 2015.

[146] S. M. Vermeulen, P. Relton, H. Grote, V. Raymond, C. Affeldt, et al., "Direct limits for scalar field dark matter from a gravitational-wave detector," Nature **600**, pp. 424–428, Dec 2021.

[147] A. Attanasio et al., "Snowmass 2021 White Paper: The Windchime Project," in Snowmass 2021, 3 2022.

[148] V. Giovannetti, S. Lloyd, and L. Maccone, "Quantum-enhanced measurements: Beating the standard quantum limit," Science **306**(5700), pp. 1330–1336, 2004.

[149] D. Ganapathy, W. Jia, M. Nakano, V. Xu, N. Aritomi, et al., "Broadband Quantum Enhancement of the LIGO Detectors with Frequency-Dependent Squeezing," Phys. Rev. X **13**, p. 041021, Oct 2023.

[150] S. Ghosh, M. A. Feldman, S. Hong, C. Marvinney, R. Pooser, and J. M. Taylor, "Combining quantum noise reduction resources: a practical approach," 2022.

[151] P. C. Humphreys, M. Barbieri, A. Datta, and I. A. Walmsley, "Quantum enhanced multiple phase estimation," Phys. Rev. Lett. **111**, p. 070403, Aug 2013.

[152] T. Baumgratz and A. Datta, "Quantum enhanced estimation of a multidimensional field," Phys. Rev. Lett. **116**, p. 030801, Jan 2016.

[153] C. N. Gagatsos, D. Branford, and A. Datta, "Gaussian systems for quantum-enhanced multiple phase estimation," Phys. Rev. A **94**, p. 042342, Oct 2016.

[154] T. J. Proctor, P. A. Knott, and J. A. Dunningham, "Multiparameter estimation in networked quantum sensors," Phys. Rev. Lett. **120**, p. 080501, Feb 2018.

[155] Q. Zhuang, Z. Zhang, and J. H. Shapiro, "Distributed quantum sensing using continuous-variable multipartite entanglement," Phys. Rev. A **97**, p. 032329, Mar 2018.

[156] W. Ge, K. Jacobs, Z. Eldredge, A. V. Gorshkov, and M. Foss-Feig, "Distributed quantum metrology with linear networks and separable inputs," Phys. Rev. Lett. **121**, p. 043604, Jul 2018.

[157] Z. Zhang and Q. Zhuang, "Distributed quantum sensing," Quantum Science and Technology **6**, p. 043001, Jul 2021.

[158] C. M. Caves, "Quantum-mechanical noise in an interferometer," Phys. Rev. D **23**, pp. 1693–1708, Apr 1981.

[159] C. M. Caves, K. S. Thorne, R. W. P. Drever, V. D. Sandberg, and M. Zimmermann, "On the measurement of a weak classical force coupled to a quantum-mechanical oscillator. i. issues of principle," Rev. Mod. Phys. **52**, pp. 341–392, Apr 1980.

[160] S. Templier, P. Cheiney, Q. d'Armagnac de Castanet, B. Gouraud, H. Porte, F. Napolitano, P. Bouyer, B. Battelier, and B. Barrett, "Tracking the vector acceleration with a hybrid quantum accelerometer triad," Science Advances **8**(45), p. eadd3854, 2022.

[161] B. Canuel, X. Zou, D. O. Sabulsky, J. Junca, A. Bertoldi, Q. Beaufils, R. Geiger, A. Landragin, M. Prevedelli, S. Gaffet, D. Boyer, I. L. Roche, and P. Bouyer, "A gravity antenna based on quantum

technologies: MIGA," 2022.

[162] L. Zhou, Z. Y. Xiong, W. Yang, B. Tang, W. C. Peng, K. Hao, R. B. Li, M. Liu, J. Wang, and M. S. Zhan, "Development of an atom gravimeter and status of the 10-meter atom interferometer for precision gravity measurement," Gen. Relativ. Gravit. **43**, pp. 1931–1942, 2011.

[163] M. Goryachev, W. M. Campbell, I. S. Heng, S. Galliou, E. N. Ivanov, and M. E. Tobar, "Rare events detected with a bulk acoustic wave high frequency gravitational wave antenna," Phys. Rev. Lett. **127**, p. 071102, Aug 2021.