R&D on quantum sensors: the DRD5 collaboration

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ABSTRACT

The detector R&D roadmap initiated by ECFA in 2020 highlighted the large number of particle physics opportunities that can be enabled by targeted and collaborative R&D in the field of quantum sensors and related technologies. Task Force 5 (TF5) of that roadmap exercise, together with the involved communities, established a list of the most promising areas for investment, and defined the R&D that would be needed to bring quantum sensors to a level that they can be incorporated into experiments. The vision outlined in the ECFA report led to the formation of DRD5 (Detector R&D 5), a global collaboration dedicated to addressing the challenges that must be overcome to realise the potential of quantum sensing for the community.

DRD5 focuses on five families of Quantum Sensors with particular suitability to particle physics, and where coordinated developments can bring about major advances in terms of sensitivity, ease of access, standardization, cost or physics reach. These are: 1) Atomic, Nuclear & Molecular Systems in Traps and Beams; 2) Quantum Materials (0-, 1- and 2-dimensional); 3) Quantum Superconducting Devices; 4) Scaled-up large ensembles of spin-oriented, hybrid or opto-mechanical elements; 5) Quantum Techniques for Sensing. These five technological domains are complemented by an overarching activity dealing with Capacity Expansion and Exchange. This document lays out the resulting high-level opportunities and common challenges that are part of pursuing the required R&D on quantum sensor technologies on a global scale.

Keywords: quantum sensors, particle physics, detectors

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Scientific Context

The European Committee for Future Accelerators (ECFA) initiated a process to develop and prepare detector technologies to address the upcoming challenges of fundamental research in the field of particle physics. The process culminated in 2021 with the publication of a detector R&D roadmap that laid out the challenges that future experiments will face [1]. The roadmap highlighted six families of detector technologies as particularly relevant to the study of nature at its most fundamental level. It stressed the importance of targeted detector R&D on these technologies, among them detectors in the realm of quantum sensing. In 2022, each of these families 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). In the course of this implementation, a new global collaboration (DRD5) was formed. The DRD5 proposal [2] outlines an R&D program for detectors in the area of quantum and emerging technologies, and was approved by the DRDC and CERN's Research Board (RB) in June 2024.

The DRD5 Collaboration is different from other R&D efforts within the ECFA framework in that it attempts to incorporate and develop the new, transformative technology of quantum sensing. The collaboration does not aim to develop and optimise known technological solutions, that often benefit from both pre-existing communities as well as a consensus on which areas are most critically in need of R&D to address future high energy physics challenges. Within DRD5, few groups have previously collaborated on R&D on a large scale in the respective areas covered by the collaboration, and there is not yet a solid consensus on which areas would be most critically in need of a dedicated effort. The new technological frontier is thus populated by a wide range of approaches being explored in a large number of institutes.

What is clear however is that for the particle physics community to optimally benefit from the very rapidly expanding quantum technologies being developed worldwide, both targeted involvement in their applications to particle physics, as well as in the technologies themselves, are crucial. This in turn requires an awareness of their potential, a dedicated workforce, and financial support for the required efforts. Furthermore, coordination of efforts is needed to minimize duplication, while a focus on developments is needed that require multiple actors to tackle issues that individual groups cannot.

The DRD5 collaboration has identified five families of Quantum Sensors with particular suitability to particle physics, but also where coordinated developments can bring about major advances in terms of sensitivity, ease of access, standardization, cost or physics reach. These families are summarized in Table 1 and expanded upon in the following sections. Tying them together is an overarching endeavor to facilitate their reach by encouraging capacity expansion and fostering opportunities and infrastructure for exchanges.

WP-1	WP-2	WP-3	WP-4	WP-5	WP-6
Atomic, Nuclear & Molecular Systems in traps & beams	*Quantum Materials (0-, 1-, 2-D)*	*Quantum Superconducting Devices*	*Scaled-up large ensembles (spin-oriented, hybrid or optomechanical devices)*	*Quantum Techniques for Sensing*	*Capacity Expansion and Exchanges*

Table 1. Families of quantum sensors (structured in form of Work Packages) and WP-spanning activities corresponding to the DRD5 proposal.

This coherent approach tackles similar challenges in widely different areas of Quantum Sensors and is well matched to the spread in group size, administrative contexts of the groups, research foci, available group resources and geographic locations of the research groups and institutes that form DRD5, a community of around 500 researchers and engineers in over 110 locations worldwide. The R&D within the six individual Quantum Sensing platforms will on one hand operate as autonomous development, discussion and exchange boards for the family-specific activities and will self-organize. On the other hand they will be in regular contact with the overall DRD5 effort, with the goal of cross-family synergies and cross-pollination.

The following sections give an overview of each Quantum Sensing family, each corresponding to a specific Work Package of DRD5. The status, challenges and expected developments over the coming years are highlighted.

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

State of the art: To maximise sensitivity to physics beyond the Standard Model (BSM) this work package encompasses several quantum sensing platforms from individual trapped ions to atom interferometers and trapped nanoparticles. Atoms, molecules, and (singly- or highly-charged) ions – including their antimatter or mixed-matter counter-parts – in traps and beams offer extraordinary measurement precision, allowing direct tests of the equivalence principle, quantum electrodynamics (QED), fundamental symmetries (e.g. Lorentz- or CPT-invariance) Dark Matter (DM) and fifth forces [3–5]. Extending the precision of atomic clocks (now below 10^{-18} [6]) to more exotic systems and across larger networks promises to dramatically increase their physics reach. Precision experiments with molecules containing octupole-deformed nuclei offer a sensitivity that is expected to enhance the sensitivity to hadronic CP violation by more than three orders of magnitude compared to current systems [7]. Likewise, atom interferometers, with outstanding sensitivity to matterwave phase shifts, can be used in equivalence principle tests, searches for BSM effects and detection of high frequency gravitational waves (HFGWs) [8–11]. Larger trapped objects such as nanoparticles also offer high sensitivity to DM [12–14] and prospects for detecting HFGWs from BSM sources [15, 16] and modifications of Newtonian gravity [17, 18].

Medium to long-term perspectives and needs:

Quantum metrology. Scaling the number of atoms N in an atomic clock or atom interferometer can reduce measurement variance as $1/N$, while entangled states can ultimately reach the Heisenberg limit of $1/N^2$ [19]. The challenge of generating entangled states that realize this quantum advantage and applying it to cutting edge measurements in the presence of noise is common to many of the technologies in this work package and promises to improve measurement sensitivity and bandwidth.

Exotic systems. Quantum control techniques including atom trapping and laser cooling that have enabled rapid progress with relatively simple atomic species need to be adapted to more complicated systems (e.g. anti-atoms, molecules, highly-charged ions, radioactive nuclei). Techniques for generating, cooling, trapping and detecting these systems are under development in various laboratories and collaborative opportunities exist to extend their applicability to a wider array of systems. For nanoparticle sensing, advances are needed in improved-efficiency loading mechanisms, low-loss materials, low-vibration cryogenics and improved optical detection.

Atom interferometry. Higher sensitivity measurements are driven by increasing the baseline in atom interferometry, requiring advanced techniques for laser cooling, large momentum transfer and atom optics [20]. Differential measurements to reduce decoherence due to classical noise sources will be essential for long baselines.

Clock networks. Phase-noise cancellation across atomic clock networks of increasing distance and complexity is an active area of research and investment that will benefit a wide range of applications including tests of fundamental physics [21]. While high-stability optical reference signals are available in several national metrology laboratories they are not broadly available to the physics community due to the need for dedicated optical links with specialized hardware. Options for distributing stable signals include improved satellite-based rf time and frequency transfer, optical fiber networks, free-space optical links and transportable standards.

Theory. More complex systems beyond few-electron atoms or ions [22, 23], require data-driven approaches and differential quantities to reduce uncertainties [24]. Several applications would benefit from more precise knowledge of nuclear properties such as shape and internal structure [25–27]. For bound systems of atoms, positronium and molecules, systematic nonrelativistic field theories are needed. Relating observables at different energy scales necessitates a meaningful relation between BSM operators with their full energy dependence. Finally, global analyses taking into account all available data in the context of various theoretical models will guide sensor and network development and interpretation of results.

Expected impact and timeline: On a timescale of 5 years, atomic clocks based on highly-charged ions, ^{229}Th and molecules will come online and search for time-variation of fundamental constants and DM signals with an up to 1000-fold improved precision. Atom interferometers at the 100 m scale will begin operation with greater atom flux and larger momentum transfer. A roadmap for larger-scale systems will be developed. In 10 years, sensitivity of EDMs is expected to be improved by several orders of magnitude bringing the realistic chance for a discovery [28]. Optical clock networks will be expanded with sensitivity below 10^{-18} inside and outside the laboratory. As a long-term goal, we envision a future worldwide network of ultrastable sensors, spanning numerous technologies providing a quantum observatory for the most fundamental processes in our universe.

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

State of the art and Scientific Context:

Quantum materials, including low-dimensional materials such as quantum dots and nanoplatelets, exhibit unique properties that can be leveraged for particle physics applications. These materials have potential uses in particle detection, particularly as scintillators, wavelength shifters, and photodetectors. However, challenges remain in scaling them to macroscopic dimensions and optimizing their properties for high-energy physics (HEP) applications. An understanding of how the material properties are affected by composition, topology and dimensions is crucial in designing specific materials that are ideally matched to particle physics requirements.

Medium to long term perspectives

Objectives: Tailoring materials for specific applications to match photodetector quantum efficiency, optimize light yield and decay time, and enhance radiation hardness. Developing extended functionalities using engineered nanocomposite materials to enable new detection concepts. Enhancing simulation capabilities by integrating quantum material interactions into Geant4 for improved modeling at the nanoscale.

Methodology: Application-Specific Tailoring (WP-2a): Identifying boundary conditions for material selection and conducting targeted R&D to develop and optimize quantum materials for detector applications. Establishing standardized protocols for evaluating performance, radiation hardness, and maintaining an open database of results. Extended Functionalities (WP-2b): Exploring larger engineered nanocomposite structures to optimize optical and detection properties. Encouraging collaboration between HEP and nanomaterials communities to develop new detector concepts. Simulations (WP-2c): Developing a Geant4 extension module for simulating quantum dot behavior, scintillator responses, and interface dynamics with host materials. Validating and optimizing the module for computational efficiency and accuracy.

Readiness and Expected Challenges: Readiness: Initial research and prototyping efforts exist, but further standardization, database development, and community-building are required. Challenges: Scaling quantum materials for macroscopic applications, ensuring radiation hardness, integrating simulations with existing tools, and fostering interdisciplinary collaboration.

Expected impact and timeline:

Activities by DRD5 in this quantum sensing field are differentiated by time scales, depending on whether they are focused on material or organizational aspects. In the short term (1-2 years), the focus is on establishing standard protocols, initiating Geant4 extension development, and building the research community. On a somewhat longer time scale, mid-term (3-5 years): the objectives are to validate simulation models, optimize material properties, and refine fabrication techniques. Finally, in the long-term (5+ years): implementing quantum materials in operational detectors and integrating findings into large-scale HEP experiments is what this work package aims to achieve.

These timelines are contingent on being able to meet the development, construction and operational costs. The project primarily involves R&D efforts, requiring funding for material synthesis, characterization, simulation development, and collaborative workshops, in particular to bring together practitioners in material sciences with particle physicists to identify the most promising directions. While specific cost estimates are not detailed, expenses will include laboratory resources, computing infrastructure, and personnel for research and validation.

3. WP-3: QUANTUM SUPERCONDUCTING DEVICE

Work Package 3 focuses on the innovation, fabrication, characterization, and refinement of ultra-low-noise solid-state sensor technology for fundamental physics.

Scientific context: Superconducting sensors are pivotal in many scientific fields and have a wide range of applications. About a third of DRD5 institutions have joined specifically for WP3, highlighting the importance of superconducting sensors in future experiments. For instance, superconducting sensors are used in dark matter searches through techniques like excitations in microwave cavities (peV to eV), superfluid He3 (GeV), light-shining-through-wall experiments (meV), and detecting individual photons and phonons in cryogenic scintillators and phonon absorbers. Phased arrays of quantum noise-limited microwave receivers are being developed for measuring neutrino mass using single-electron Cyclotron Radiation Spectroscopy. Superconducting devices have been demonstrated for single electron mass spectroscopy and statistical beam characterization over $1 - 2$ keV without electron optics. At higher energies, superconducting arrays have been developed for proton beam measurements (10–100 GeV). These devices have numerous applications in fundamental physics, providing unique benefits.

Technology: superconducting sensors refers to a broad technology base, including passive and active devices (TES, KID, SPA, SNSPD, STJ, TWPA, SQUID) that can form large integrated circuits using materials like Nb, NbN, NbTiN, Ti, Ta, Al, Mo, W, Hf, and Ir, along with proximity structures and tunnel junctions. These devices can be fabricated on various substrates using oxides and normal metals. For example, they can be integrated with micromachined structures on Si for reading ultra-low-noise micro-mechanical cantilevers or with spin systems, such as implanted impurities, to study quantum dynamics. In astrophysics and astroparticle, superconducting technology has achieved a high degree of sophistication, with large detector arrays used in harsh environments for science-grade observations. In other areas of fundamental physics, however, the technology is less mature, requiring focused efforts to increase TRL and create rugged, easy-to-use sensors for large-scale experiments. Challenges include packaging, metrology, longevity, and environmental susceptibility such as EMI, magnetic noise, and cosmic ray sensitivity.

Medium to long term perspectives: Over the next 20 years, physics applications of superconducting sensors will grow significantly, with the technology unlikely to be displaced for decades. To advance, communities must collaborate. The particle physics and low-noise devices communities should regularly communicate to understand needs and solutions. At the device level, recent advances in quantum measurement, information theory, quantum complexity, and emergent phenomena offer opportunities to create new device types. Superconducting devices are uniquely positioned to exploit concepts like squeezing, back-action evasion, and entanglement due to the BCS state. Practically, it is necessary to develop optimized schemes to couple targets to probes (e.g., electromagnetic couplers, phonon coupling to elastic fields, liquid gases, superfluids, spin systems, particle beams, micro-mechanical systems). At the microscopic level, engaging material scientists and chemists is crucial to understanding device fabrication and operation, including yield, uniformity, and reproducibility. Studying microscopic physics that determines device behavior, such as speed, noise, and impurities, is essential. At the systems level, engineers must help build user-friendly experiments, especially in interface control. Understanding backgrounds in specific applications, such as thermal noise, stray light, and phonon noise, is vital. This aspect ties into the development of measurement techniques like noise analysis, linearity, dynamic range, stability, 1/f noise, quantum efficiency, and error quantification.

Expected impact and timeline: The innovation of new experimental techniques, consolidation of the technology base, and enhancement of TRL require diverse expertise. WP3 seeks to foster strong links between organizations and individuals who have not previously collaborated on addressing some of the most challenging problems in standard-model physics.

4. WP-4: SCALING UP "QUANTUM"

Quantum sensors typically operate at the single-sensor level, typically around the nanometer scale, but many applications in high-energy physics, dark-matter searches, and gravitational wave detection require these systems to be scaled up. This Work Package deals with this challenge, and it is divided into the following subpackages:

- **Massive spin-polarized ensembles** Massive spin-based detectors fall into three main categories: (1) Levitated ferromagnetic torque sensors [29] are highly sensitive to local fields and to ultra-low energy bosonic fields. These sensors require advances in superconducting readout electronics and vacuum purity. (2) Molecules with radionuclides are used for searches for a permanent electric dipole moment of the electron (eEDM) and probing BSM physics beyond 10 TeV, an overlap with the exotic systems of WP-1. (3) Large, highly nuclear spin-polarized samples are of great importance for nuclear magnetic resonance-based axion and axionlike particle dark matter searches, similar to the Cosmic Axion Spin Precession Experiments (CASPEr) [30–33], and spin-dependent fifth force searches (e.g., QUAX-$g_p g_s$ and ARIADNE [34, 35]). Progress in this area depends on expanding species range, increasing spin density and volume, as well as improving polarization techniques.
- **Hybrid devices** Confinement at the nanoscale creates artificial atoms with tunable properties, enabling novel active fast scintillators based on quantum dots [36]. Engineering bulk materials and nanomaterials for high-energy physics requires advances in stopping power, radiation hardness, large-scale integration, and speed. Ensembles of heterostructures offer the tunability and improvements through work function engineering for nanowire-based photocathodes and for low-dimensional materials for gas detectors. Heterodox technologies, such as DotPix [37], quantum-enhanced silicon detectors, and opto-mechanical sensors, should enhance detection capabilities. Scaling these advances for high-energy physics necessitates collaboration between material scientists and detector developers to bridge the gap between novel materials and large-scale detector integration.
- **Opto-mechanical sensors** Mechanical systems are widely used for precision measurements, including quantum sensing applications [38, 39], and can be scaled to macroscopic regimes. The motion of individual mechanical sensors has been probed at the standard quantum limit – where measurement uncertainties are reduced to the level where measurement imprecision and quantum mechanical back-action are equally significant. Going beyond this limit will revolutionize technologies like atomic force microscopy, which relies on quantum-limited optical readout for semiconductor industry applications, and levitated nanosphere force sensing, which achieves zeptonewton (10^{-21} N) sensitivity [40]. These mechanical systems offer promising avenues for probing fundamental physics, including dark matter detection [14, 41–50], neutrino searches [51], gravitational wave detection [15, 16, 52, 53], and Lorentz symmetry tests [54]. Promising quantum technologies include resonant mass detectors using low-loss solids [44, 48], levitated particles [42], MEMS [49], optical cavities [55, 56], and superfluid helium-based sensors [57, 58]. Macroscopic quantum superpositions might also be used to test if gravity can entangle systems [59, 60], e.g. by having two one-micron-sized diamonds in a spatial superposition with a superposition distance of 100 microns. Such a gravity-induced entanglement could be used to test the quantum nature of gravity. Further development is needed to optimize their sensitivity and design, with quantum sensing and entangled sensor networks offering paths to surpass current limitations and uncover new physics [61].

Expected Impact and Timeline

For each subpackage, it is key to identify the resources, collaborations and research infrastructures needed to advance the experimental performance of these systems. The long-term impact is expected to not only aid searches for new physics but also quantum technologies in general. Within the near-term future, these questions should be explored in workshops, with a particular focus on how to optimise networked quantum sensors. In the longer term, prototypes and proofs-of-concept should be developed and tested.

5. WP-5: QUANTUM TECHNIQUES FOR SENSING

Measurements are intrinsically limited by the noise level set by the Heisenberg Uncertainty Principle. This sets the sensitivity limit that can be achieved with a given sensor, which for systems that rely on classical resources is referred to as the Standard Quantum Limit (SQL). While operating at the SQL can provide the required sensitivity level for a given application, searches for new physics and particles beyond the standard model, as well as precision measurements of fundamental constants, often require sensitivities beyond the SQL. Through the use of quantum techniques, one can engineer and manipulate the quantum state of a system to evade the SQL. These techniques can enable instruments with much higher sensitivities that can detect tiny perturbations to quantum systems to improve the science reach of fundamental science experiments.

Quantum Techniques

- *Squeezing:* Squeezed states are characterized by noise levels below the SQL in one observable at the expense of added noise in the conjugate one. Their use as probes in measurements results in a detection noise floor below the SQL as long as the quantity being measured aligns with the observable that is squeezed [62]. One of the great successes is the use of squeezed light to enhance gravitational wave detectors. In addition to gravitational wave detection, squeezed states can also be used to enhance optical interferometers to detect strain due to wavelike dark matter [55, 63], optomechanical resonators to search for vector-like ultra-light dark matter fields [49] and particle-like dark matter when scaled up to a large array [64], etc.

- *Back-action evasion:* Any measurement of a quantum system will lead to a perturbation referred to as 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. Techniques known as back-action evasion seek to minimize the impact of measurements on the observable of interest. These techniques have been implemented in a number of experiments, in particular those associated with optomechanical sensors. For these sensors, 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. This has recently been implemented for the LIGO experiment [65].

- *Entanglement:* While techniques such as squeezing and back action evasion offer the possibility of enabling 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 a/N (as opposed to $1/\sqrt{N}$ for classically connected quantum sensors), where N is the number of entangled sensors and a is constant that depends on experimental imperfections [66–72], for applications that require measuring a linear superposition of the measurements made by all the sensors in the array. This is the case, for example, for ultra-light dark matter signals [73].

- *Optimization of physics reach:* Leveraging quantum resources to their full extent will require theoretical studies to fully understand different sensing strategies and identify applications to high energy physics. 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. In addition, these strategies need to be extended to be robust to experimental imperfections and noise.

Expected Impact and Timeline

Over the past decade, innovative strategies employing non-classical measurement techniques have been demonstrated to surpass the SQL in individual sensors. Further developments over the next 5-10 years aim to increase the quantum sensing advantage and realize an even greater advantage in systems consisting of networked quantum sensors (see, e.g., Ref. [61] for a recent example using entangled arrays of optomechanical sensors). The development of quantum-enhanced sensors and quantum networks of these sensors promises enhanced sensitivity capabilities that can be leveraged in searches for gravitational waves, dark matter, and broader new physics beyond the Standard Model.

6. WP-6: CAPACITY BUILDING

The mission of Work Package 6 is to structure and provide substantive support to the incipient multidisciplinary community that is working on the R&D of quantum sensing technologies for frontier experiments. The capacity-building activity relies on four pillars: inclusivity, education, knowledge platforms, and shared infrastructures. The main challenge is to unite a diverse community with different working and interaction cultures; from the large collaborations of high-energy accelerator physics to experiments at the scale of an institute or university laboratory run by a small team. The unification concept relies on providing adequate cooperation tools in the form of standardized agreements and privileged access to shared infrastructures to the participating institutions.

The construction of a new community working together on problems related to Quantum Science is an opportunity to prepare a proper ground where equity, inclusivity, and diversity are rooted in its foundations. We believe that the transversality of this collaboration within the scientific community and its connection to society makes this aspect instrumental in unleashing its maximum scientific potential and advancing scientific excellence in society. These objectives can only be achieved when the collaborators develop a feeling of belonging to the collaboration.

The main actions and activities of WP6 in the next years include:

- Design of an information exchange platform that will include characteristics of techniques and novel materials and their potential uses (client-producer specifications), as well as a list of available expertise and skills of different participating groups connecting technical capabilities within the collaboration.
- Preparation of standards for screening and characterization of materials and devices via shared infrastructure and facilities.
- Building an educational and development platform – including schools and workshops– for developing a workforce familiar with the potential and challenges of quantum sensors.
- Adapting existing educational programs to ensure comparability of skills and curricula, upskilling existing professionals to increase multidisciplinarity, and education based on microcredentials instead of 4-year study plans.
- Preparation of intra-collaborator template agreements to provide access to the dedicated specialized infrastructures within the collaboration, together with the definition of standardized interfaces to allow different test set-ups to benefit from facilitated access.

Expected Impact and Timeline

WP6 will be actively pursuing support of transversal activities that do not have as a goal to achieve a specific technological or scientific purpose but to create an inclusive, healthy, and fruitful substrate that fosters cooperation and cross-fertilization in the domain of quantum sensing. This also includes the consolidation of the workforce in the field by supporting career paths both in research and the private sector focused on R&D in quantum sensing by specific actions targeting mutually beneficial cooperation. It is crucial to remember that the DRD-5 collaboration aims to bring incipient technologies to a high level of TRL. This requires supporting not only the initial steps, rooted in fundamental research, and the final stages at the last levels, but also intermediate steps which require intensive engineering work and prototyping. Multidisciplinary cooperation resolves many of the barriers to developing the technologies but is insufficient to overcome all the technical challenges. A sustained and focused funding scheme is required to complete the full cycle of technological development.

7. EXAMPLE APPLICATIONS FOR QUANTUM SENSORS

WP-1

Example 1: Networks of atomic clocks can be used to search for ultra-light dark matter [74] and macroscopic dark-sector objects [75]. Such networks may include ground-based clocks in laboratories and transportable clocks, as well as space-based clocks on satellites (such as in GNSS networks). In searches for variations of fundamental constants induced by ultra-light dark matter [76, 77], the use of N nodes in the network can boost the sensitivity to dark-matter signals by a factor of $\sqrt{N}$ when the coherence length of the dark-matter field is at least as large as the size of the network [74] (or by the larger factor N if the nodes are quantum entangled, see WP-5).

Example 2: Exotic atoms, such as positronium [78] and muonium [79], provide ideal platforms to probe bound-state quantum electrodynamics (QED) due to their simple two-body nature and lack of a hadronic nucleus. The cleanness of these exotic systems also makes them excellent probes of new forces and particles beyond the Standard Model [80, 81]. Yet-to-be-discovered true muonium (bound state of a muon and an anti-muon) promises further exciting opportunities in the future [82, 83], as do novel matter-antimatter atomic and ionic systems. Precision laser spectroscopy of these systems can both search for BSM physics as test QED in the strong field regime.

WP-2

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 [84].

Example 2: 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 with 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.

WP-3

Example 1: Ultra-low-noise thin-film superconducting devices are central to the advancement 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: 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 for HEP 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.

WP-4

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 mechanical sensors that leverage quantum techniques such as squeezed light readout and back action evasion. The idea is to search for 1D tracks of excited sensors left in a 3D sensor array. Such a detector would be sensitive to dark matter particles at around the Planck mass ($10^{28}\,\mathrm{eV} \approx 20\,\mu\mathrm{g}$).

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 leverage available quantum resources.

WP-5

Example 1: Optomechanical, electromechanical and magnetomechanical 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 opens up the possibility of further enhancements through collective measurements of multiple quantum-coherent sensors, as demonstrated by Ref. [61]. 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 [85]. 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" [86, 87], with the signal/noise ratio being proportional to the number of sensors (see WP-5).

8. EXECUTIVE SUMMARY

The field of high energy physics has traditionally engaged in long-term international collaborative efforts on detector R&D to address the numerous challenges posed by the very large and costly devices needed for the relevant experiments. DRD5 will make full use of this targeted and structured approach to explore 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, both for table-top experiments as well as for large-scale apparatuses, on a global scale.

Instead of addressing the needs of individual areas of particle physics, the DRD5 effort focuses on a set of Work Packages that the conveners and the communities (the "signatories") have identified as being potentially, specifically, or broadly relevant, and that would benefit from *targeted* and *collaborative* R&D efforts on a *global* scale. Such a collaborative effort can 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.

Going beyond the state of the art in Quantum Sensing for particle physics and to explore new phase space in terms of Physics Beyond the Standard Model requires a willingness to address common challenges and requirements, those beyond specific application or experimental needs. For this reason, DRD5 has focused on areas where advances will benefit a wide range of diverse communities, by identifying - for five different families of Quantum Sensors - a small number of areas that will greatly benefit from a concerted effort, and that will enable existing technologies to take the next step. Many of the technological developments targeted in DRD5 come with the promise of opening up new phase space for BSM physics or of improving existing devices by expanding their functionality or sensitivity. Such efforts, however, require sustained and reliable funding.

Support at the national level for work on Quantum Sensing for Particle Physics is essential in order to fully achieve the potential of quantum technologies for a broad and fundamental impact on particle physics. The support is required to advance the five Quantum Sensor families that DRD5 focuses on, but also in order to develop an expert workforce through specific university programs, to ensure the fluid exchange of expertise, and to ensure efficient sharing of and access to infrastructure on a global level.

Financial support is needed for both the workforce and on the technical fronts; **the possibility of leveraging such support to achieve major advances in Quantum Sensors for Particle Physics is tightly tied to the fostering of open exchanges, to a willingness and ability to pool resources and to work across disciplines and borders.**

9. APPENDIX 1: SIGNATORIES

DRD5 consists of groups from the following 112 institutes (in alphabetic order by country):

Australia: University of Western Australia; Swinburne Univ. of Technology
Austria: IQOQI Vienna; Atominstitut, TU Wien
Canada: McGill University; TRIUMF
China: IHEP Beijing
Croatia: Institute of Physics, Zagreb
Czech Republic: Czech Technical University; University of West Bohemia: New Technologies – Research Centre, Pilsen; Charles University - Faculty of Mathematics and Physics
Finland: Helsinki Inst. Physics; VTT
France: OBSPM / SYRTE; Laboratoire de Physique des Lasers, CNRS-Université Sorbonne Paris Nord; Laboratoire Kastler Brossel, Paris; ILM Université Lyon 1; IRFU / CEA, Université Paris-Saclay
Germany: Ulm University; Leibniz Universität Hannover; Physikalisch-Technische Bundesanstalt (PTB); KIT, Karlsruhe; TU Munich; DESY; GSI / Helmholtz Institut Jena; MPP Garching Germany; HU Berlin; FBH Berlin; University of Heidelberg; University Düsseldorf; Universität Tübingen; Universität Bremen / ZARM ; Semiconductor Laboratory of the Max Planck Society, Garching; TU Darmstadt; Helmholtz Institute, Johannes Gutenberg University Mainz; Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)
India: Inst. of Engineering & Management (IEM), Kolkata; IITT, Tirupati; TIFR, Mumbai; University of SOA, Bhubaneswar; Lovely Professional Univ. Punjab
Iran: Isfahan University of Technology
Israel: Technion IIT, Haifa
Italy: University of Pisa and INFN; INFN Pisa; University / INFN - Pavia; INFN Padova; INFN LNF (Frascati); INFN TIFPA (Trento); INFN Lecce; INFN Torino; INFN LNL (Legnaro); INFN Roma 1; University/INFN - Florence; University / INFN Milano-Bicocca; Fondazione Bruno Kessler Trento; IOM CNR & Elettra Sincrotrone, Trieste; University / Politecnico / INFN - Bari; Univ. Roma 1 (Sapienza); Univ. Roma 3; Univ. of Napoli; CNR-SPIN Institute; INFN Roma Tor Vergata; University of Camerino (Unicam)
Japan: QUP / KEK; University of Tokyo / ICEPP; Kyoto University; Shizuoka University
Korea: Korea University
Mexico: Universidad de Aguascalientes
Netherlands: University of Groningen & Nikhef
Norway: University of Oslo
Poland: Warsaw University of Technology; National Centre for Nuclear Research (Narodowe Centrum Badan Jadrowych) Warsaw; Nicolaus Copernicus University (UMK) Torun
South Africa: University of Cape Town
Spain: University Zaragoza; IFIC (CSIC - University of Valencia); University of Lleida; Universidad Politécnica de Cartagena; Institute of Structure of Matter, Consejo Superior de Investigaciones Científicas (CSIC), Madrid
Sweden: University of Stockholm
Switzerland: University of Geneva; University of Zürich; ETH Zürich; CERN
Taiwan: National Taiwan University and Academia Sinica
Türkiye: Sabanci University, Istanbul; Düzce University, Düzce; Accelerator Technologies Institute, Ankara University, Ankara
UK: Oxford University; University of Warwick; University of Birmingham; NPL; University of Southhampton; Imperial College; University of Sussex; University of Manchester; University of Liverpool
USA: Arizona State University; University of Arizona; UCLA; MIT; Northwestern University; Yale; ORNL; Caltech; NIST (Time and Frequency Division); LBNL; Univ. of Delaware; FNAL; SLAC

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