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

(signatory list in Appendix 1)

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 and consequently 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 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 need to address. This roadmap highlighted the importance of targeted detector R&D in a range of areas relevant to particle physics, 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 chapter 5 of the ECFA roadmap dedicated to quantum sensors and related technologies.

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 (general overview: chapter 4; individual WP's: chapters 5–10). Each high-level Work Package will be introduced by a short overview of the physics cases where relevant, and each sub-WP will be discussed in more detail, including a targeted time line and milestones. An overview of the required and of the available resources is provided for each WP.

Collaborative, organizational, and intellectual property-related issues are addressed in chapter 11. 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 a solid consensus on which areas would be most critically in need of a dedicated effort. To address these two points, a workshop including experts from all six areas covered in the ECFA roadmap's chapter 5, and incorporating proposals submitted by the wider communities in response to a call sent out 10 weeks prior to the workshop, took place at CERN from Apr. 3–6, 2023. 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 from Oct. 2–4, 2023, as well as on continuous input from the corresponding communities, but must be considered an evolving document. The structure itself of the collaboration (outlined in chapter 11) 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 always 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, and from which both the field of quantum technologies and the field of particle physics can benefit.

We wish to emphasize here that both 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 a national scale have demonstrated that such an approach can result in tangible benefits: the AION collaboration [1] for example has played a pioneering role in defining standardized approaches for detection of gravitational waves and for searches for dark matter using terrestrial vertical atomic interferometric devices. The involved shared engineering effort has resulted in a significant acceleration of building times, in the availability of a set of identical devices at lower cost, and in improved reliability through standardization. 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 during the ECFA roadmap development, in that rather than structure the discussions around physics domains and list the most salient challenges in those areas that roadmap had identified as high-impact physics targets, or 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)	
Exotic systems				E,T		
Atom interferometers				X		
Clock & signal distribution	X			X		
WP2 *Quantum Materials*		X X	X X			X X
0-, 1-, 2-D materials		X	(X)		X	X
Superconducting devices & electronics at 4K		X				(X)
WP3 *Large ensembles of quantum sensors*						
multi-modal systems						
indirect readout						
WP4 *Scaled-up "Quantum for HEP"*		X	(X)	X	(X)	X
spin-sensitive devices		X		X		X
hybrid devices						X
WP5 *Quantum Techniques for Sensing*	X	X	X	X	X	
Squeezing						
Entanglement	X	X	(X)	X	(X)	
Back action evasion						
WP6 *Capacity-driven design*	X	X	X	X	X	X
schools & training						
networks of expertise						
shared infrastructures						

Table 2: High-level work packages (built on identified global challenges) and their overlap with the quantum sensor families of the ECFA detector R&D roadmap. Where experimental (E) and theory (T) aspects are not differentiated, a general overlap (X) is indicated.

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

This work package covers three large areas: exotic systems (such as Highly Charged Ions - HCI's - or Rydberg systems or radio-isotopes), atom interferometry (with a focus on their potential for dark matter searches and their sensitivity to gravitational waves) and clocks (atomic, 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 BSM physics or for violations of fundamental symmetries rely on probing a wide range of systems (trapped atoms, ions, molecules, 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 HCI's, 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		

Table 3: Quantum sensor families impacted by R&D in WP-1a

5.1.1 Physics driver

Atoms, molecules and (possibly highly charged) ions 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) [?], which can also be carried via Ramsey spectroscopy of gravitationally bound quantum states of ultra-cold neutrons [?]. Diatomic molecules are the focus of several attempts to improve the limits on the EDM of the electron (ThO, HfF+, RaF), with first exploration of the potential of poly- atomic molecules to improve sensitivity even beyond those systems [?]; 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 [?], with the potential of a further order of magnitude in sensitivity.

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 HCI's), 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_b), but vice-versa, being able to access a system with 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 eEDM searches, with a reach in terms of SUSY sensitivity beyond 10 TeV masses. Given the overlap with WP 4, but also the fact that these mostly (but not exclusively) are investigated in small numbers, this category will be treated here.

What is needed for this category are improvements to existing experiments, new trapping technologies, advanced quantum control (including cooling techniques) of molecules, 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 "Beam to beaker to beam". Here, efforts on portable Penning and/or Paul traps with extremely high vacuum are particularly relevant.

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 [2], test bound-state QED calculations, and measure nuclear properties [3, 4]. When the number of equations exceeds that of free parameters, one can search for new physics at the accuracy frontier (see e.g. [5, 6, 7, 8]). The physics reach is forever at the level of the larger uncertainty between experiment and theory.

At present, the output, i.e. values 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 in this front. Specific examples include the muon mass [9], Rydberg constant [10], deuteron charge radius [11], and theoretical predictions of the muonium Lamb shift [12] and gross structure [13]. Together with ongoing experiments [9, 14], improved calculations would enable an independent determination of the muon $g-2$ [15], crucial in order to shed light on the recently confirmed deviation between experiment and theory [16]. Considering other simple systems, effort is needed to better exploit measurements of bound-electron g-factors [17, 18, 19], transitions in molecular ions [20, 21], and the energy levels of helium [22, 23, 24] and helium-like ions [25, 26]. On top of more refined "pure" QED calculations, there is a growing need for a better understanding of the internal structure of nuclei [27], and how it affects observables in atomic physics [28, 29]. These are especially pronounced in compact systems such as exotic atoms (see e.g. [30, 31] and references therein), and in the interpretation of hyperfine structure measurements [32, 33].

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 [34]).

- A robust, broadband search for new physics must also allow for the consistent estimation of fundamental constants in the presence of new physics [35].

5.2 WP-1b : Interferometry

The nascent field of atom interferometry has a wide potential range of fundamental physics applications, ranging from gravitational wave detection, searches for ultralight (wave-like) dark matter candidates and dark energy, to precise tests of the Standard Model (e.g., measuring the fine structure constant), and tests of quantum mechanics. In light-pulse atom interferometry, laser pulses are used to coherently split, redirect, and recombine matter waves.

In a gradiometer configuration, two 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 [36].

State-of-the-art atom interferometers are currently operating at the 10-meter scale, e.g. at Hanover, Stanford and Wuhan. Larger-scale detectors ranging from 100-m to km lengths will be required to detect gravitational waves from known sources, and there are plans for 100-meter experiments at Fermilab (MAGIS), in France (MIGA) and in China (ZAIGA). The Atom Interferometric Observatory and Network (AION) project envisages a staged Atom Interferometry program, starting with a 10-m device and progressing via a 100-m experiment, which could be located at the Boulby mine in the UK or at CERN, to a 1 km instrument. AION will enable exploration of the properties of ultra-light dark matter (DM) and gravitational waves (GWs) from the very early Universe and astrophysical sources in the mid-frequency band ranging from several mHz to a few Hz.

To advance the field, issues common to metrology and spectroscopy have to be addressed, in particular the measurement of time or frequency with very high accuracy (related to WP-1c).

5.3 WP-1c : networks, signal and clock distribution

Numerous individual and locally / nationally linked high precision devices relying on a wide range of quantum sensing systems exist world-wide. In order to achieve the next level of sensitivity, either to transform the individual nodes into a globally linked single detector, or to link heterogeneous devices into a single multi-modal device (allowing to constrain different putative BSM models that affect individual nodes differently) or to provide a global reference signal against which local nodes can be calibrated or compared to, this work package combines collaborative efforts along two main lines 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 4: Quantum sensor families impacted by R&D in WP-1c

5.3.1 Physics drivers

Since atomic clock frequencies are defined by the laws of nature and the fundamental constants, these measurements are exceptional probes of fundamental physics. They test the symmetries of nature, such as Lorentz-invariance, and provide probes for BSM physics, such as the nature of dark matter. Already individual atomic and molecular clocks exhibit high sensitivity to BSM effects and variations of fundamental constants, and many groups are already driving the precision of these systems ever forward.

However, building a global network of high-stability and high-accuracy clocks is beyond the possibilities of individual research entities and 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 such as for ultralight dark matter or topological defects traversing a multi-node mesh. Secondly, sending standardized optical clocks to off-mesh sites on Earth or in space would 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, where multi-node meshes would ensure greatly reduced systematics. It should also be pointed out that such a very large scale clock network would also greatly benefit other fields, such as VLBI astronomy using radio telescopes, or can help pave the way towards VLBI optical astronomy.

5.3.2 WP-1c_a: Large-scale clock network

World-wide efforts towards developing ultra-precise clocks based on a wide variety of systems (different atomic elements, ions or molecules or even nuclei) are pushing the precision of clocks to below 1 part in 10^{18}. 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, that would allow spreading 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. High temporal-resolution (to O(10 ps)) time stamping on a global scale will result in a set of Earth-sized highly sensitive detectors for all possible types of quantum sensors.

The two aspects (high precision time-stamping to O(10 ps) and distribution of a highly precise continuous clock signal to provide a reference) are closely linked.

Where are we? What do we need to happen?

This WP pursues two approaches. On one hand, it builds on an existing design study (CLOck NETwork Services) to go beyond current single point-to-point connections between a few partners, mainly relying on national initiatives. There is a strong case for cross-national collaborative efforts to extract a higher value out of the individual existing parts and to extend this network towards further institutes. Addressing technical issues (HW for L-band needs to be developed, test dedicated (dark) and existing LCG network fibers, switching bands between countries at borders (cross-border links)) 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 satellite-based systems.

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).

It has been possible to demonstrate the transmission of quantum information over more than 500 km without the need of any repeaters. Some of these new protocols require sub-nanosecond synchronisation such as the one that can be offered by the CERN technology White Rabbit, currently allowing synchronization at the ns level. It's 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 programme Alt PNT.

Figure 1: Existing and future trans-national 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.

Where are we? What do we need to happen?

For neutral species, magneto-optical traps rely on provision and control of the trapping and probing lasers and of the magnetic field generating infrastructure.

For charged species, either Paul or Penning traps would be suitable, bearing in mind that vacuum limitations may constrain the lifetime of any transported species. Penning-trap based devices relying on superconducting solenoids to address this issue are under construction, while alternate approaches with permanent magnets are still at a conceptual level and their feasibility must be established. Paul trap based devices, in which the RF can help mitigate neutralization of positively charged ions, are limited in the number of different species that can be trapped simultaneously.

In both cases, UHV vacuum systems, uninterruptible power supplies, gate valves, device transportabilty and cost are additional aspects. A standardized approach relying on miniaturization and established readily available components would be greatly beneficial.

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

WP-1a (exotic systems)

WP1a_a (exotic systems)) →	milestone 1 → deliverable 1	milestone 2 →	milestone 3
WP1a_b (calculations) →	milestone 4 →	milestone 5 deliverable 5 →	milestone 6
WP-1b (interferometry) →	milestone 7 deliverable 7 →	milestone 8 →	milestone 9
WP-1c (clocks)			
WP1c_a (clock networks) →	milestone 10 deliverable 10 →	milestone 11 →	milestone 12
WP1c_b (portable clocks) →	milestone 13 →	milestone 14 →	milestone 15 deliverable 15

6. WP-2 : QUANTUM MATERIALS

6.1 WP-2a : 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 from their bulk analogues due to quantum phenomena and can thus be considered the building blocks of “quantum materials”. They are also often used as converters (wavelength shifter, ionizing particle to optical photons, photons to electrons....) and through incorporation into sensors therefore offer great potential for future detection technologies. WP2 focuses on exploring the role these components can play as elements of more complex dedicated assemblies such as those in WP5.

6.1.1 WP-2a_a: 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 later constitutes targeted R&D towards materials that are optimally matched to existing and extrapolated device requirements. Such R&D thus encompasses e.g. developing nanodots whose emission properties are matched to the quantum efficiency of photodetectors, optimizing the luminescence properties of nanodots (brightness, 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 HEP is their radiation hardness. Whatever the intended application, one of the prerequisites for the use of e.g. quantum dots or perovskytes in calorimetry for high-energy physics is firstly 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 performances from a wide range of active groups, a standardized comparison procedure is desirable. As exemplified in the case of scintillation performances, a common protocol (x-ray induced decays and emission, relative scintillation yield, transmission) would allow evaluating performances against radiation, and would enable to set up and maintain an open database of these performances, similar to that set up 30 years ago at Lawrence Berkeley National Lab (https://scintillator.lbl.gov/inorganic-scintillator-library/). Establishing such evaluation and fabrication protocols is a necessary first step, while populating the corresponding databases would need to be implemented after each measurement campaign.

6.1.2 WP-2a_b: Extended functionalities

Larger engineered structures (at the O(1$\sim$10 μm) scale) have properties that are defined not only by their composition, but also by their geometries, internal layout or applied fields and 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 (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.

6.1.3 WP-2a_c: 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), this medium being discontinuous at small scales: an effective medium description is thus not suitable. First initiatives [37] 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.

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

Table 5: Quantum sensor families impacted by R&D in WP-2a

6.2 WP-2b : Cryogenic systems

Superconducting technology is essential for observational astronomy for next generation telescopes in the IR$\sim$mm wavelength, but also for x-ray astronomy. Devices consist not only of single (kilo-pixel) detectors but also require complex superconducting electronics. Engineering of superconducting materials to control T_c, but also their other properties (e.g. bi-layers or multi-layers). Very high vacuum is essential for the UHV sputtering processes, as are a number of further performance characteristics of any resulting device.

work package	clocks & networks	super-conducting	kinetic sensors	atoms/ions/ molecules	opto-mechanical	nano-engineered / low-dimensional
WP-2b_a (4K stage)		X	X			(X)
WP-2b_b (detection)		X				
WP-2b_c (integration)		X				

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

6.2.1 Physics drivers

From the point of view of particle physics, the extreme sensitivity of superconducting detectors, whose sensitivity level is provided by the energy required to break Cooper pairs, or on exploiting the long-range order of the coherent superconducting state, is well matched to very low energy phenomena. Superconducting devices are thus a very promising approach for a direct determination of the neutrino mass scale via, for example, high resolution and high statistics measure- ments of low-energy electron capture and beta decay spectra. Although measuring the absolute neutrino mass is extremely challenging, having the aim to detect an extremely tiny spectral distortion in the end-point region of beta and electron capture spectra in an energy scale much less than 1 eV, R&D for superconducting quantum sensors is very well motivated given that we know that there is a lower bound for neutrino masses.

Overall the opportunities for creating a new generation of fundamental physics experiments based on superconducting electronics is substantial. Areas such as combining superconducting devices with micro-machined accelerometers and mechanical resonators is 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 inevitably 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. 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-2b_b), in the requisite electronics (WP-2b_a) or in the integration into easily usable devices (WP-2b_c) are required.

With a focus on the intermediate TRL developments, the following technologies are then needed:

- single photon detection (incl. at microwave frequencies)
- ultra-low-noise amplifiers, high temp (4K) ultra-low-noise amplifiers, chip-based systems for generation and detection of squeezed states over microwave to mm wave range.
- solid state superconducting detectors for high-energy photon and massive particle detection and spectroscopy, such as single-electron detection
- development of packaging methods for superconducting electronics (e.g. magnetic field shielding, cosmic ray shielding, stray light shielding, EMI, ...)
- multiplexing technology challenges for superconducting mega-pixel devices
- materials science challenges

These can be grouped into three areas around which the three sub-WP's of the superconducting WP are arrayed:

- Theme 1: superconducting electronics for microwave-mm-wave range
- Theme 2: high-energy particle detection (photons & massive particles)
- Theme 3: characterization and measurement methods (including packaging and screening techniques to stop photons reaching the detector)

As an example for Theme 2, but also for the inter-relatedness of the three themes, we consider the case of R&D on TES/KIDs:

- the optimization of TES/KIDs based light detectors to further enhance their sensitivity (e.g. through the Neganov-Trofimov-Luke effect) and time resolution (through the investigation of novel materials and geometries);
- the development of a compact and radio-pure cryogenic wiring. 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 voluminous.
- the development of a multiplexed readout for TESs, to minimize the number of channels and the heat load on the cryostat. This will not be 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.
- a new DAQ/storage/trigger system to deal with the much higher data rate of these fast sensors compared to the standard cryogenic calorimeters, and to integrate these data with those obtained from the cryogenic calorimeters.

It should be noted that because of the requisite development / customization costs and a relatively small user base, these developments will not be driven by industry. We also recall that these enabling technologies could have a transformative impact also on other devices, such as superconducting quantum bits, quantum sensors and cryogenic amplifiers.

6.2.2 WP-2b_a: The 4K stage

Some (slight) overlap with DRD4 (detection of keV photons) and DRD7 (calorimetry).

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

Where are we? What do we need to happen?

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.

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), FPGA's are needed. Furthermore, complementing these elements with tunable circuit elements and understanding along with a more profound comprehension of material science considerations at 4K are needed.

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 withing the 4K domain.

6.2.3 WP-2b_b: Cryogenic quantum sensors for particle and photon detection

microwave photons, axion detection,...also fall into this section

While already a mature technology in the field of observational astronomy, 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 [38], pionic [39] , and kaonic [40] 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. Furthermore, their use is tied to the use of ultra-low temperatures (dilution refrigerators).

Where are we? What do we need to happen?

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 ions storage rings and muon beams, and space-based detectors like the TES detectors that will be deployed in the ATHENA project.

- exploration of the use of high T_C TES-like detectors for easier integration in existing and future cryogenic (but not necessarily sub-K) environments
- 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 reference [?], 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.

6.2.4 WP 2b_c: Resilient integration of superconducting systems

resilience against perturbation (high E,B), noise, packaging, stray-light avoidance, cosmic rays, interfacing

Stafford

Where are we? What do we need to happen?

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

Milestones are underlined, deliverables are in *italic*.

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

WP2a_a →	characterization protocol →	database definition →	populated db
(application-specific tailoring)	*protocol*	*database prototype*	*functional db*
WP2a_b	milestone 4	milestone 5	milestone 6
(extended functionalities)		*deliverable 5*	
WP2a_c →	status & desiderata →	parallel developments →	benchmarked simulations
(simulations)	*report*	*simulation SW designs*	*specific simulations*

WP-2b (Cryogenic systems)

WP2b_a →	milestone 10 →	milestone 11 →	milestone 12
(electronics at the 4K stage)	*deliverable 10*		
WP2b_b →	milestone 13 →	milestone 14 →	milestone 15
(calorimetry, particle detection)			*deliverable 15*
WP2b_c →	milestone 16 →	milestone 17 →	milestone 18
(resilient integration)			*deliverable 18*

Example1: Work on improved formulation, characteristics and radiation resistance of perovskites or other nanodots can result in novel functionality for existing HEP devices, such as the possibility of determining shower shapes within future "chromatic calorimeters".

Example2: Thin film technologies for high T_C superconductors open up the possibility of operating corresponding superconductor-based quantum sensors (SNSPD's, TES's, MMC's, ...) at easily accessible temperature ranges that do not require dilution refrigerators. Already now, MgB_2-based SNSPD's operate at temperatures higher than 10K.

7. WP-3: DEVELOPMENT OF LARGE ENSEMBLES OF QUANTUM SYSTEMS

Very rapid progress in building e.g. arrays of TES sensors has been achieved in recent years. Scaling up other quantum devices in a similar fashion, to achieve large surface area or large volume devices, including devices which couple e.g. mechanical and optical degrees of freedom, is the focus of this WP. Related to this is the readout of such devices without a concomitant increase in readout channels. Approaches such as transduction, broadband response of arrays of TES's with slightly different resonance frequencies, mapping of detector-element specific responses onto a modality that allows parallelization of readout are among those also investigated in this WP.

7.1 WP-3a: Multi-modal devices (e.g. Opto-mechanical systems, transduction)

A signal induced in a sensor is often not read out directly. In a crystal calorimeter, energy deposits are converted into light that is detected with a photodetector that converts the collected photons into an electrical signal that is measured. In the realm of quantum sensors there are many area of transduction. In impulse metrology a tiny displacement of a mechanical resonator is often measured through interferometry of laser beams. Transduction from microwave to optical frequencies is also heavily deployed. In optomechanical systems the limitations of microwave (GHz) piezo-optomechanical devices need to be overcome to increase their sensitivity. Spin-photon interactions can be measured through optical interrogation of the spin states or through magnetometry. Spin defects in 2D materials offer the potential for integration into hybrid quantum systems. The relative ease of tuning defects in 2D materials and their heterostructures via stacking, nanoscale patterning, selective doping, and strain engineering make these material systems attractive for the creation of quantum transducers.

7.2 WP-3b: Quantum-system-inspired parallel readout

Cryogenic detector arrays, such as TES, face the same challenge as other greatly scaled-up detector ensembles, that of readout of such large structures. Contrary to the sequential readout that probes each detector element individually one after the next, these systems have focused on development of efficient global readout by identifying the specific element of the ensemble that has seen a signal through the effect of that element on the electrical properties of the specific circuit coupled to that element. Specifically, resonance parameters of a large number of circuits (each with slightly different resonance parameters) are probed in parallel, resulting in a "comb" of frequencies. A change in one element will change the resonance frequency specific to that element on the time scale of the detector element response. Such approaches are used in e.g. satellite-based TES photon detectors [**?**] or continuous readout of the Square Kilometer Array [**?**].

Adapting such an approach to other high granularity (spatial and / or temporal) detector technologies by associating each detector element to an element-specific local readout circuit, and probing the global multispectral response of the overall ensemble of detector elements is daunting, but could allow alleviating some of the challenges of existing. sequential (readout time) or parallel (number of readout channels, and thus required services) readout approaches, effectively leading to a "Quantum DAQ". Issues such as triggered or collision-linked readout (in the case of High Energy physics accelerator-based systems) or of designing element specific circuits (in the case elements are not solid-state based) will need to be addressed.

Work Package	clocks & networks	super-conducting	kinetic sensors	atoms/ions/ molecules	opto-mechanical	nano-engineered / low-dimensional
WP-3a (multi-modal devices)			(X)		X	X
WP-3b (quantum-inspired R/O)		X			(X)	X

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

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

WP-3a (multi-modal devices)

WP3a ⟶ milestone 1 ⟶ milestone 2 ⟶ milestone 3

deliverable 1

WP-3b (Indirect readout)

WP3b_a ⟶ milestone 7 ⟶ milestone 8 ⟶ milestone 9

deliverable 7

8. WP-4: SCALING UP "QUANTUM"

Typical quantum sensing systems are at or below the nanometer or single sensor scale while, at least for high energy physics applications but also for enhanced sensitivity of e.g. levitated macroscopic systems, 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, in such a manner that a very large fraction of the spins are aligned or 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 [41], graphene mono-layers [42] 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 by combining established technologies from different fields, such as Quantum Cascade lasers with silicon position sensitive detectors, or incorporating scintillating nanodots into tracking devices (DotPix) [43] 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

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 eEDM

- large volume, high density, highly spin-polarized samples (for HEP and exotic spin-dependent samples, but also magnons)

Where are we? What do we need 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 already exists.

What is needed is development beyond state-of-the-art (superconducting) readout electronics, much better vacuum, purity/flux trapping of superconductors needed 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 SUSY 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.

Thirdly, production of polarized "targets" and CASPEr - like experiments benefit from large compact samples of spin polarized systems. Both going to lower temperatures (from 4K down to 10mK) and to larger sample size (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, LHe_3, 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). In this context, the usefulness of bulk 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 (DRD1, DRD6) and for photon detection (DRD2, DRD4), the scintillation behavior of systems consisting of small numbers of atoms results in drastically changed behaviors that justify a dedicated WP. Confinement results in artificial atoms, such that nanowires, nano-platelets, mono-layers, Perovskites, 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 or possibly by coupling quantum cascade lasers to silicon detectors, 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 do we need 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 overall low energy deposits by minimal 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 engineering may allow for increased QE with examples being demonstrated by composite photocathodes with coatings of atomicially thin graphene or BN. Graphene monolayers on photocathodes increase the work function (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 [43], 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.

Scaling in the number of entangled sensors is being pursued in the area of impulse metrology, where the measurement of rapid and minute impulses allowing for the detection of forces across a wide range of frequencies. This technique is being used 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 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 ties to WP2 for the development of materials. Read-out, 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 do we need to happen?

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

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

WP-4a (spin-polarized ensembles)

WP4a → milestone 1 → milestone 2 → milestone 3
deliverable 1

WP-4b (Hybrid systems)

WP4b_a (spin ensembles) → milestone 4 → milestone 5 → milestone 6
deliverable 4

WP4b_b (heterostructures) → milestone 7 → milestone 8 → milestone 9
deliverable 7

WP4b_c (heterodox devices) → milestone 10 → milestone 11 → milestone 12
deliverable 10

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). Through the use of quantum technologies, however, one can engineer and manipulate individual quantum states, 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 / optimization)	X			X	(X)	
WP 5b (entanglement)	X			X	(X)	
WP 5c (Heisenberg limit)	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 state, often a continuous wave light beam is used. These beams also have quantum descriptions 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, quantum uncertainty 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 the quadratures of the field, either the phase (or amplitude), while simultaneously increasing the noise in the orthogonal property — amplitude (or phase) — hence "squeezing" the minimum uncertainty. 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 increases the sensitivity of the optical measurement at the output of the kilometers-long laser interferometer.

9.2 WP-5b: Entanglement

In the discussions leading to establishing global Work Packages, entanglement has not played a prominent role, although it is clear that entangled photon sources are already being used and hold great potential for even more sensitive devices than those whose development is proposed below in this proposal. While this topic did not feature prominently in the proposals submitted in the course of the run-up to the DRD5 implementation workshop in April, 2023, subsequent input from different communities has highlighted both its importance and interest.

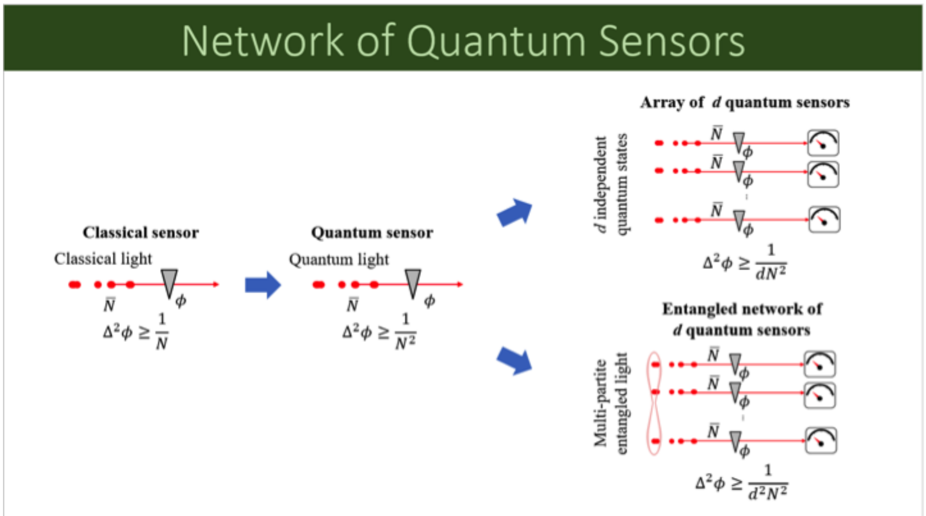

Figure 2: The improvement in sensitivity that entanglement can bring to a set of individual nodes of quantum sensors scales with the number of nodes.

When considering optical interferometery using multiple-photon states, a quantum description is generally employed using mulitple entangled photons. The most common manner by which to achieve entangled photons is through process known as spontaneous parametric down conversion. Spontaneous parametric down conversion is a nonlinear optical process, where one photon incident on a nonlinear crystal can transformed into two photons. The incident photon is known as the “pump” photon, one of the output photons is known as the “signal” photon, and the other output photon is known as the “idler” photon. The transformation of the pump photon into signal and idler photons follows conservation of energy and momentum. For applications in which a large photon flux is needed, these entangled stated can be extended beyond pairs of photons. The use of entanglement for quantum sensing becomes particularly relevant for an array of sensors, in which case it allows for a significantly more favorable scaling in sensitivity (reduced uncertainty in estimation) with the number of sensors, as shown in Figure 1. Such an array of sensors requires the distribution of entanglement. The simplest distribution of this quantum resource between a fixed pair of destinations uses a source of entangled beams of light, which then are sent to the two locations. This transmission from a single source 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.

The DRD5 / RDq process seeks potential proposals on how the high level Work Packages could incorporate developments targeted towards implementing entanglement at-scale, given the expected commensurate gains in sensitivity.

9.3 WP-5c: 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 [44] 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. Squeezed light and backaction evasion can be used to reduce the measurement-induced noise below the SQL. 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 [45]

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 applicable to particle physics. For examples, the classic papers by Carl Caves and colleagues have been instrumental in incorporating quantum techniques in the LIGO experiment [46, 47]. 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 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. 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)

what is the modest end goal (5 years from now)?

and then work backwards (annually)

WP-5a (squeezing) →	milestone 1 deliverable 1 →	milestone 2 →	milestone 3
WP-5b (entanglement) →	milestone 4 deliverable 4 →	milestone 5 →	milestone 6
WP-5c (back action evasion) →	milestone 7 deliverable 7 →	milestone 8 →	milestone 9
WP-5d (physics optimization) →	milestone 10 deliverable 10 →	milestone 11 →	milestone 12

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 on needs and capabilities;
- 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 requires building a 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. 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, 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-6b: Education platforms

Advancements in applications based on the quantum properties of systems require interdisciplinary approaches. Currently, most higher education institutions offer specialization in 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.

]textcolorredDiversity has to be part and parcel of the education efforts.... To address these challenges, the following three pillars are considered to be crucial:

- upskilling existing professionals to increase multidisciplinarity
- education based on microcredentials instead of 4 year study plans
- unification of skills in the existing programs

Where are we? What do we need to happen?

10.2 WP-6c: 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.

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-6d: 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) remains 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 standardized interfaces to allow different test set-ups to benefit from that access.

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

WP-6a (Education)

WP6a $\longrightarrow$ milestone 1 $\longrightarrow$ milestone 2 $\longrightarrow$ milestone 3

deliverable 1

WP-6b (Exchange platforms)

WP6b $\longrightarrow$ platform structure $\longrightarrow$ platform implementation $\longrightarrow$ wide adoption

structure description

WP-6c (Shared infrastructures)

WP6c $\longrightarrow$ prototype agreement $\longrightarrow$ milestone 8 $\longrightarrow$ milestone 9

interface standard

11. CROSS-DISCIPLINARY CONNECTIONS OF DRD5 WORK PACKAGES

The proposed Work Packages are not all independent of each other; in fact, several WP's rely on progress made in other WP's 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 techniques)	-	X	X	?	(X)	X
WP 2 (Quantum systems in traps and beams)	X	-		?		X
WP 3 (Quantum materials)	X		-	?	X	X
WP 4 (Large sensor ensembles)	?	?	?	-	?	X
WP 5 (Scaled-up bulk systems for mip's)		(X)	X	?	-	X
WP 6 (Capacity building)	X	X	X	X	X	-

Table 11: Work Package cross-influences and impacts

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, but also university, local and potentially industrial funding) and 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 (DRDC) host and the collaboration, and very light-weight, standardized addenda to the MOU that detail that group's contributions that will be signed by a representative of an individual group, CERN's director of research, and the spokesperson of DRD5 / RDq. This approach is matched to the spread in group size, administrative contexts of the groups, research foci, available group resources and geographic locations of the groups. Platform = discussion / exchange board for WP and sub-WP

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 in form of:

- a **Management Board** (one spokesperson, one representative from each of the 6 Working Groups (the top-level WP coordinators)); 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.

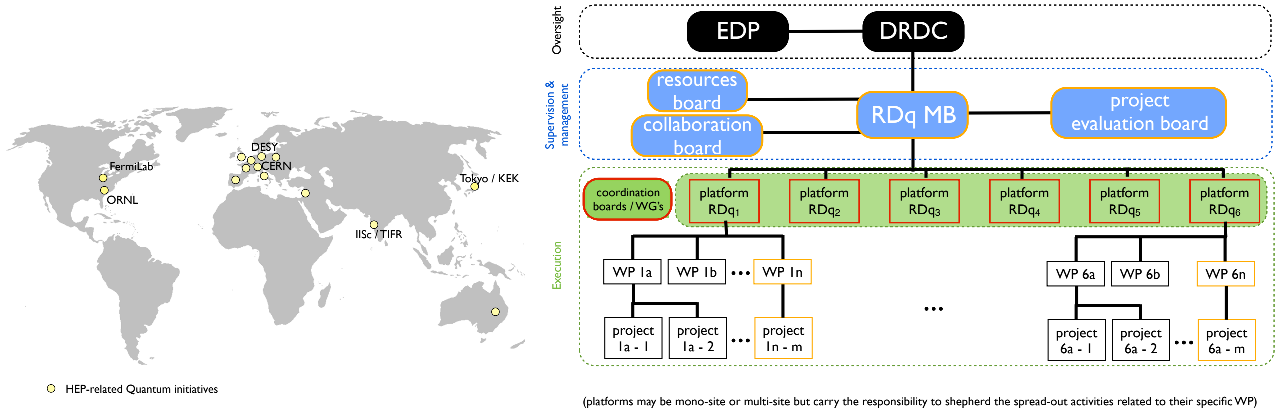

Figure 3: Left: Geographic distribution of possible Work Package coordinators. Right: Collaboration organigram

- a **Collaboration Board** consisting of the WP- and sub-WP coordinators from the 6 Working Groups; an equal number of Quantum Sensor family representatives elected by all participants; and a number of national representatives (one per participating country) appointed by the national funding agencies.
- an elected structure consisting of experts from within the Collaboration that forms a **Project Evaluation Board** that has the expertise to evaluate any projects submitted to it by groups of at least 3 collaborating groups for scientific merit and against the overarching goals of the ECFA roadmap and the existing WP's.

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. Figure 3 summarizes the foreseen organizational forms.

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, whose role is to coordinate efforts related to the specific Work Packages world-wide, to provide progress reports to the Collaboration Board and the Management Board, and to act as a shepherd for additional activities related to the specific Work Packages and sub-WP's 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-WP's; the sub-WP coordinator's responsibility is limited to the specific sub-WP. As the groups involved in a specific sub-WP's 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 WP's 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 / 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 regarding 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 base-line 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 the case the Collaborator from whom the IP stems leaves the Collaboration. Given the worldwide interest 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 inappropriate to this Collaboration.

12.5 Resources and responsibilities

The responsibilities and resources for the targeted WP's are distributed on a global scale. The following two tables provide a snapshot of the institutes currently active in the technology area of the different work packages and having expressed an interest in furthering their goals towards the aimed-for milestones, as well as providing an overview of the involved (available and additionally required) resources.

Table 12 summarizes the expressed interests to be involved in specific WP's by individual institutes. This list is by no means exhaustive and will evolve over time.

institute	WP-1	WP-2	WP-3	WP-4	WP-5	WP-6
name		X	X	X	X	X

Table 12: Mapping of institutes to Work Packages (expression of interest)

Table 13 summarizes the available resources and additionally needed resources for each WP (per annum, over the next 5 years) within the DRD5 / RDq collaboration.

WP	FTE (available)	budget (available, M€)	FTE (additional need)	budget (additional need, M€)
WP-1				
WP-2	2.5	0.15	2.5	0.15
WP-3	2.5	0.15	2.5	0.3
WP-4	2.5	0.15		0.2
WP-5	0.5	0.05		
WP-6				

Table 13: Estimate of annually *available* resources (financial, manpower) within the DRD5 / RDq collaboration and annually *additionally required* needs (financial, manpower) over the next 5 years to tackle the individual WP's.

13. SIGNATORIES

In the following, the list of signatories to the above document is provided, together with 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.

13.1 Conveners (alphabetic ordering)

Hiroki Akamatsu (KEK), Etiennette Auffray (CERN, Geneva, Switzerland), Caterina Braggio, Florian Brunbauer (CERN, Geneva, Switzerland), Shion Chen, Martino Calvo, Marcel Demarteau, Michael Doser (CERN, Geneva, Switzerland), Christophe Dujardin, Andrew Geraci, Arindam Ghosh, Glen Harris, David Hume, Derek F. Jackson Kimball, Jeroen Koelemeij, Georgy Kornakov, Stefan Maier, Gobinda Majumder (TIFR, Mumbai, India), Alberto Marino, Tanja Mehlstäubler, Alessandro Monfardini, Ben Ohayon (Technion IIT, Haifa, Israel), Nancy Paul, Sadiq Rangwala (RRI, Bangalore, India), Florian Reindl, Mariana Safronova, Swati Singh, Stafford Withington, Steven Worm

13.2 Signatories (on 1.1.2024) ordered by country and geographical region

Europe:

Americas:

Asia:

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