Quantum Sensing for Dark Matter and Gravitational Waves

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Abstract

Searches for wave-like dark matter can benefit from efforts to develop experimental sensitivity beyond the Standard Quantum Limit. In particular, RF cavity experiments and spin magnetometers are promising technologies in this endeavour. In recent years, it has been shown that experiments of this kind can also be sensitive to high-frequency gravitational waves. As part of the community input to the European Strategy for Particle Physics 2026 update, we report on the activities and plans of some experimental and theoretical groups aiming to search for dark matter (and gravitational wave) signals beyond the Standard Quantum limit. Our report is not exhaustive in cataloging the efforts of experimental or theoretical groups in Europe, but presents the current status and plans of the CASPEr, GNOME, GravNet, MAGO, RADES and SRF Heterodyne collaborations.

1 Scientific Context

One of the major outstanding limitations in the Standard Model (SM) of particle physics is the absence of a microscopic candidate of dark matter (DM). Multiple experimental tests to confirm or exclude theories of DM have been conducted, with many more being proposed. Experimental tests depend acutely on the mass of the dark matter particle, which is unknown and could span many orders of magnitude, from 10^{-20} eV to over 100 TeV [1–3]. For masses in the range 10^{-20} eV to ~ 1 eV, DM particles need to be bosonic in nature [4–6]. As a consequence, they behave like a classical field as opposed to a collection of individual particles. This class of DM candidates, often termed "wave-like" or "ultralight", generate coherent effects that lend them to searches using detectors operating at or near the limit imposed by quantum mechanics on the ability to measure small signals. This limit is often known as the "Standard Quantum Limit" (SQL). Many existing experiments operate at or near this limit (see, e.g., [7–12]).

Dark Matter Theory. Well-motivated wave-like dark matter candidates include the QCD axion that solves the strong CP problem [13–16], pseudoscalar axion-like particles (ALPs) [17–27], massive dark photons [28–30] and ultralight scalars [31, 32]. The conditions determining the parameter space of greatest theoretical interest differ depending on the candidate.

In the case of the QCD axion, there is a concrete prediction for the relation between its mass and the strength of its coupling to SM fields. If the axion symmetry allowing a solution to the strong CP problem is broken before inflation, the misalignment mechanism predicts that axions can make up the DM abundance in a wide region of parameter space [33–35]. On the other hand, if the axion symmetry is broken after inflation, the resulting network of strings dominates axion production, leading to a specific prediction of the axion mass corresponding to DM. However, our ability to simulate the evolution of the axion string network is limited, meaning that the best available predictions encompass a range of masses [36–39].

For ALPs, the misalignment mechanism and modifications thereof [33–35, 40–45] can produce the correct DM abundance in a wider region of parameter space than the canonical QCD axion. Assuming a radiation-dominated universe, experimental observations constrain the mass to lie in the range $10^{-21}\,\mathrm{eV} \lesssim m_a \lesssim 100\,\mathrm{eV}$ for $\mathcal{O}(1)$ initial misalignment angles.

Multiple production mechanisms for dark photon DM have been proposed [46–52]. Recently, it has been pointed out that restrictions might apply on the parameter space in which dark photons can constitute all of DM [54–58].

Ultralight scalars can also constitute all of DM. Their couplings to the SM are typically strongly constrained by searches for violation of the equivalence principle or by atomic clocks over much of their parameter space (see, e.g., [59]). RF cavities and spin systems, the primary experimental methods discussed in this document, are typically less sensitive to this type of DM, therefore we do not discuss them further here.

Searching for the DM coupling to electromagnetism (EM) is often the dominant experimental search method. Some of these candidates can also couple to other quantities, such as fermion spin in the case of the QCD axion, ALPs and dark photons.

In the case of axion or ALP couplings to EM, the relevant Lagrangian term being tested is $\mathcal{L} \supset -(1/4) g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$. The coupling $g_{a\gamma\gamma} = \alpha_{\mathrm{EM}} C_\gamma / (2\pi f_a)$ is defined with respect to the axion decay constant f_a, and C_γ is a model-dependent parameter. In the case of QCD axions, $(f_a \times m_a)$ is fixed by solving the strong CP problem, but C_γ remains model-dependent. In the case of ALPs, both f_a and C_γ are free parameters.

In the case of axion or ALP couplings to fermions, the relevant interaction Lagrangian is $\mathcal{L} \supset g_{a\psi\psi} \partial_\mu a \bar{\psi} \gamma^\mu \gamma^5 \psi$, where the coupling $g_{a\psi\psi} = C_\psi / f_a$ is related to the axion decay constant via a model-dependent parameter C_ψ.

For dark photons, the coupling to the SM depends on the gauge symmetry of the additional boson. The canonical dark photon is kinetically mixed with the SM photon through a term $\mathcal{L} \supset \epsilon/2F_{\mu\nu}F'^{\mu\nu}$, where ϵ denotes the strength of the kinetic mixing, and $F'^{\mu\nu}$ is the dark photon field strength tensor. Other uses of the term "dark photon" can apply to, e.g., $B-L$ gauge bosons, or other gauged SM symmetries. In this case, the dark photon coupling is of the form $\mathcal{L} \supset g_X A'_\mu J^\mu_X$, where X denotes the gauged SM symmetry and J^μ_X is the associated current.

Gravitational Waves. Many production mechanisms for gravitational waves (GWs) exist at supra-kHz frequencies, most of which involve physics beyond the SM. These were recently reviewed in [60]. GWs produced in the early universe have direct implications for particle physics, as they typically involve new fields beyond the content of the SM. Furthermore, the correlation between the peak frequency of emitted GWs and the temperature of the universe at emission implies that measuring high-frequency GWs directly informs us of new physics at scales inaccessible to colliders.

It has been shown that approaches to detect ultralight dark matter can also have sensitivity to GWs, usually in a frequency range above that which is accessible to existing detectors [61–66]. The GW frequencies accessible to ultralight DM detectors typically sit in the range where no astrophysical GWs are expected, and any positive measurement would correspond to new physics. If a stochastic background of early universe GWs were detected, it would mean probing energy scales greater than $\Lambda \gtrsim 10^{10}$ GeV. However, owing to the weakness of the gravitational coupling, detecting the expected signal might require going beyond the current sensitivity of these detectors, and in particular, going beyond the SQL [67].

Detector Theory and Experimental Status. The weakness of the expected couplings between DM and SM fields requires the use of detectors with extremely low noise levels. They also require the use of extremely low-noise amplifiers and other electronic equipment. In some cases, the detector chain operates at or near the SQL. However, to probe certain ranges of well-motivated DM masses and couplings, going beyond the SQL is required.

For QCD axion searches with RF cavities, the need to go beyond the SQL is straightforwardly understood. In a traditional axion haloscope, the SQL implies that there is at least one photon in the signal bandwidth, so that the background photon rate $dN_b/dt \propto f/Q_a$, where f is the frequency of the signal, and Q_a is the axion "quality factor", related to the formally well-defined axion coherence time (see, e.g., [68] for a recent quantification of the microphysical origin of this timescale). Meanwhile the signal photon rate $dN_s/dt \propto (B_0^2 V)Q_{\rm cav}$, where B_0 is the applied magnetic field, V is the useful cavity volume and $Q_{\rm cav}$ is the cavity quality factor [69]. The background rate therefore increases linearly with signal frequency, while the signal rate decreases like $1/f^{11/3}$ due to the fact that $V \propto 1/f^3$ and $Q_{\rm cav} \propto 1/f^{2/3}$ as a result of $Q \propto V/S\delta$, where S is the surface area and δ is the skin depth. For typical cavity parameters, the signal rate drops below the noise photon rate happens at frequencies of $f \gtrsim$ GHz, corresponding to masses of $m_a \gtrsim 4\,\mu$eV. Going beyond the SQL would push that crossover to higher frequencies/masses.

ALPs have an even faster drop-off in the signal rate at high frequencies than the QCD axion searches. The signal rate scales as $dN_s/dt \propto 1/f^{17/13}$ for fixed $g_{a\gamma\gamma}$, implying that the need to go beyond the SQL is greater for generic ALPs than for the QCD axion. The kinetically-mixed dark photon signal rate in an RF cavity decreases as $1/f^{11/3}$, so the ability to probe a given kinetic mixing parameter ϵ is also diminished at high frequencies/DM masses.

Similar arguments can be made for spin-based DM searches. In this case, quantum mechanics implies a minimum amount of "spin projection" noise. This limit arises from the non-commutativity of spin components in different directions, implying that measurement of spin in one direction introduces noise in the other. The result is that the sensitivity to a signal scales as $1/\sqrt{N_{\rm spins}}$ at the SQL. This imposes a limitation on spin-based axion searches that prevents reaching the QCD axion prediction for much of the parameter space [70]. To test the QCD axion prediction in the entire frequency range accessible to NMR searches therefore requires going beyond the SQL.

The classical limitations of GW detectors at high frequencies have recently been quantified [67]. Harnessing quantum resources to go beyond the SQL enables significant sensitivity with modest classical resources, potentially allowing experimental tests of cosmogenic GW signals with significant implications for particle physics.

2 Objectives and Methodology

The primary objective of the theoretical and experimental work described in this document is clear: detect a signal associated to dark matter. A secondary objective is to detect a gravitational wave signal. Tertiary objectives include setting world-leading constraints on as much dark matter and gravitational wave parameter space as can be achieved on a realistic timescale. Case-by-case objectives are described below.

2.1 CASPEr

The Cosmic Axion Spin Precession Experiment (CASPEr) [71] uses nuclear magnetic resonance (NMR) to search for a spin torque induced by interaction of axionlike particle (ALP) dark matter (DM) with the nuclear spins of macroscopic spin ensembles. In this text we report the work of the CASEPr-gradient branch of CASPEr [72], located in Mainz, Germany. It is sensitive to the gradient coupling of ALPs, g_{aNN}. The CASPEr-electric branch [71, 73–76], located in Boston, USA, now moving to Johns Hopkins University in Baltimore, USA, is sensitive to the nuclear electric dipole moment (EDM) coupling g_d in addition to the gradient coupling.

The goal of CASPEr is to search for ALP dark matter in the mass range between approximately 10^{-12} eV and 10^{-6} eV. Estimates show that projected sensitivity to g_{aNN} in the scan mass range can reach $\sim 10^{-14}\,\mathrm{GeV}^{-1}$, going beyond the constraints placed by astronomical observations.

The interaction between spins and ALPs can be represented by a pseudo-magnetic field oscillating at the ALP-Compton frequency [71, 75]. In the experimental setup, superconducting magnetic coils provide a bias field for the sample. If the bias-field strength is chosen such that the Larmor frequency matches the ALP-Compton frequency, the pseudo-magnetic field drives the spins into resonance, causing the magnetization vector to tilt and precess around the bias field. The magnitude of the signal detected by the sensor increases with the nuclear polarization of the sample. CASPEr-gradient uses hyperpolarization techniques in preparing samples to optimize sensitivity [77].

We use two apparatuses to investigate the regimes of low-frequency ALPs (up to ~ 1 MHz) and high-frequency ALPs (up to ~ 600 MHz): with the low-field setup (generating a bias field of $0 - 0.1$ T), the ALP signal is detected by a Superconducting Quantum Interference Device (SQUID), the state-of-the-art magnetic-field sensor, which operates effectively up to ~ 4 MHz. With the high-field setup (bias field of $0 - 14.1$ T), the signal is detected by an induction coil.

2.2 GNOME

The Global Network of Optical Magnetometers for Exotic physics searches (GNOME) is an international collaboration aiming to detect transient signals from exotic fields associated with ultralight bosonic dark matter (UBDM) and other beyond-the-Standard-Model (BSM) scenarios [78–80]. GNOME utilizes a geographically distributed network of time-synchronized atomic magnetometers (and more recently, comagnetometers [81, 82]) operated in magnetically shielded environments. The network is designed to identify globally correlated pseudo-magnetic signals resulting from the passage of exotic field configurations through the Earth [83, 84].

The principal scientific target of GNOME is axion-like particles (ALPs), including topological defects such as domain walls [83, 85], bound-state structures such as axion stars or Q-balls

[84], and virialized halo fields [86]. The magnetometers are sensitive to spin-dependent couplings of ALPs to nuclear and electron spins, which can be described by linear and quadratic gradient interactions [80]. These couplings produce transient Zeeman-like energy shifts analogous to magnetic fields, but with distinctive spatial and temporal signatures. The use of a network enables rejection of local noise and false positives, and allows for the identification of spatiotemporally correlated signals consistent with astrophysical origins.

Recent upgrades under the *Advanced GNOME* program include the development and deployment of self-compensating noble-gas–alkali-metal comagnetometers [81, 82], which significantly enhance the network's sensitivity (by up to two orders of magnitude for neutron couplings) and provide discrimination between magnetic and non-magnetic spin interactions. Advanced GNOME stations also expand the parameter space probed to include exotic couplings to neutron and electron spins, complementing the original proton-spin sensitivity [80].

While GNOME was initially conceived as a dark matter detection network [78, 83], the experiment's architecture makes it a natural platform for detecting exotic signals from bursts of ultralight bosonic fields emitted during cataclysmic astrophysical events such as black hole mergers [87, 88]. These exotic low-mass field (ELF) bursts would generate distinctive chirped spin-precession signals in the GNOME network [88], potentially probing phenomena at energy scales beyond the reach of conventional laboratory searches for exotic physics.

The collaboration has completed five Science Runs, with the most recent incorporating hourly calibration pulses, environmental monitoring, and glitch-rejection algorithms [80]. The current science program includes data analyses targeting ALP domain walls, ALP stars, Q-balls, stochastic halo fluctuations, gravitationally focused streams, and solar-bound axion halos. Methodologically, GNOME has used or plans to apply matched-filter searches for coherent transients, intensity interferometry techniques for stochastic fields [89], and cross-correlation of global signals to enhance sensitivity to weak, non-repeating events.

GNOME represents a mature and continually evolving platform for discovery-oriented searches for BSM physics.

2.3 GravNet

The overarching goal of the GravNet project is to develop, test and deploy a novel experimental platform that could enable the first detection of gravitational waves (GWs) in the frequency range of MHz to GHz, thereby providing a new and unique window into astrophysical processes that have so far eluded observation. The use of cavities in strong magnetic fields has been identified as one of the most promising techniques to search for high-frequency gravitational waves [62, 63]. So far, efforts were focused on cavities with small volumes that are tuned to search for axion-like particles. By contrast, the GravNet scheme is based on combining different technologies and methodological approaches to measure synchronously cavity signals from multiple devices in magnetic fields operated as a network across Europe, increasing the sensitivity to high frequency GWs (HFGWs) by several orders of magnitude compared to current approaches. In this way, GravNet will open up a new, vast parameter space for gravitational-wave searches and might be the enabling step towards the first detection of HFGWs. GravNet will primarily consist of one cavity with TM012 resonance frequency of 270 MHz, six cavities with main resonance frequencies of 5.4 GHz as well as six cavities with main resonance frequencies of 7.7 GHz, distributed over experimental sites in Frascati, Bonn, Mainz and Villigen. The GravNet collaboration has participants from the Universities of Bonn and Mainz, INFN and ICREA/IFAE, and it aims at expanding to all interested institutions worldwide to benefit from the possibilities of a more extensive network. It received funding from an ERC Synergy Grant 2024.

2.4 MAGO

The MAGO proposal, initially a CERN-INFN collaboration, now continued as a DESY-FNAL effort, uses a loaded superconducting RF (SRF) cavity to search for gravitational waves. The primary target is gravitational waves in the kHz to MHz range. As originally proposed in [90] and revisited in recent work [64], this experiment can have a GW noise-equivalent strain sensitivity on the order of $(S_h)^{1/2}(f) \gtrsim 10^{-21}/\sqrt{\text{Hz}}$ in the targeted frequency range.

The basic operational principle is similar to that of traditional resonant mass detectors for gravitational waves, as the primary GW interaction occurs with the SRF cavity walls. However, the readout method differs significantly, resembling laser interferometers but using RF modes instead of optical ones. The SRF cavity is driven at a specific resonant frequency f_0, which interacts with the cavity walls' vibrations induced by the GW. This electromagnetic-mechanical coupling generates a signal at $f_0 \pm f_{\text{GW}}$. The MAGO cavity can operate in two modes: (1) a resonant mode, where $f_0 \pm f_{\text{GW}}$ matches another cavity resonance $= f_1$; or (2) a broadband mode, where $f_0 \pm f_{\text{GW}}$ does not correspond to a resonant frequency, but the readout bandwidth is wide enough to detect signals across a range of f_{GW}. The broadband mode is most analogous to the operation of LIGO.

2.5 RADES

RADES collaboration is composed of CERN, CAPA – University of Zaragoza, Universidad Politécnica de Cartagena, ICC – Universitat de Barcelona, Yebes Observatory, IFIC (CSIC – University of Valencia), ENS – CNRS, Aalto University, Karlsruher Institut für Technologie, Max Planck Institut für Physik, Instituto Tecnológico de Aragón, University of Mainz and ICMAB – CSIC.

Within RADES experiments, its high frequency (8 – 18 GHz) proposal combines single-photon detection (SPD) by means of 3D transmons (cavity-qubit systems), tuning by means of ferrimagnetic materials and the use of high temperature superconductors (HTS) to enhance the sensitivity of the axion dark matter detection in the 30 - 70 μeV mass range. The experiment is planned to be located at the Canfranc Underground Laboratory (LSC) to leverage that low-radiation environment, which could improve the performance of the SPD.

Focusing on noise reduction, a new path by evading the limitations to sensitivity imposed by the Haus-Caves theorem for the added noise of linear phase-preserving amplifiers [91] is taken. By using a quantum single-photon counter (QSPC) it is possible to exploit instead the phase-number uncertainty principle to relegate all measurement backaction into the irrelevant phase variable [92], [93]. The equivalent noise of a QSPC-read haloscope, assuming dominated exclusively by the thermal photon emission in the cavity, not only can bypass the SQL of a conventional heterodyne linear amplifier readout, but it exponentially drops for decreasing temperatures below TSQL, until eventually limited by the shot noise of low counting (Poisson) statistics. Depending on the integration time, this limit can well be 3 or 4 orders of magnitude below SQL-equivalent levels, something that would unlock an impressive improvement in sensitivity. At this point we want to remark the contribution of RADES collaboration at ERC-SyG DarkQuantum project.

RADES also plans to develop a low-frequency (200-500 MHz) axion haloscope to be installed in the bores of the BabyIAXO magnet, profiting from the large magnetic volume available. Equipped with quantum-limited sensors and cooled down to cryogenic temperatures (few tens of mK) the setup would offer very promising sensitivity prospects in the 1 - 2 μeV range [96].

Moreover, both high and low frequency proposals aim to explore the detectability of HFGWs through the inverse Gertsenshtein effect [94]- [61], analyzing the sensitivity of RADES cavities [97] and developing prescriptions to design and simulate RF cavities for optimal sensitivity to HFGWs.

Summing up, the main goal of the work is the development of a quantum single photon counter (QSPC) based on superconducting qubits (transmons) arranged to perform quantum non-demolition (QND) measurements of the photons in the cavity, and made with novel high-B-compatible designs. Other objectives are: 1) an innovative tuning system based on a ferromagnetic crystal hybridized with the cavity mode, 2) an improved Q factor with the use of HTS coatings in the inner cavity wall, and 3) advanced quantum algorithms for accelerated qubit readout.

2.6 SRF Heterodyne

The SRF heterodyne approach to axion detection was a new theoretical concept proposed in [98, 99] (see also [100]). Multiple collaborations worldwide are now pursuing this approach. In Europe, the efforts are being undertaken at CERN as part of the quantum technology initative (QTI). The working principle is similar to traditional haloscopes, in that the axion encounters a background EM field and converts into photons that are then searched for resonantly. The difference with respect to standard haloscopes is that the background EM field is AC, oscillating at a frequency f_0. Therefore, the signal appears at $f_0 \pm m_a/(2\pi)$. The main advantage of this approach lies in dissociating the cavity size from the testable axion mass.

A 2-mode SRF cavity will be designed and built to optimise the axion-background mode coupling. At CERN, a non-mechanical tuner will be used to cover a $\sim 100\,\text{kHz}$ range of axion masses in the prototype device. Low-noise RF instrumentation will be used for the pumping of the background cavity mode, and the readout of the signal mode.

2.7 Theory

Various initial studies have been undertaken to examine quantum resources and protocols that could allow for experimental sensitivity beyond the SQL. For example, entangling cavities [101], employing squeezed vacuum states [7], phase-sensitive readout [102] and other approaches [103, 104] have all been considered. A unified description of the signal, detector response and losses, and limitations of possible quantum resources is not yet available. An objective on this front is to produce such a unified description that properly accounts for imperfections in the detector and readout chain.

Starting from the Lagrangian, the Hamiltonian of the system can be obtained, including all loss ports, input and output modes. Quantifying the performance of the measurement technique or resources being used to go beyond the SQL usually requires computing the Quantum Fisher Information (QFI). This quantity can be computed for various different approaches and used to compare them on equal footing.

3 Readiness and expected challenges

3.1 CASPEr

CASPEr-gradient has finished the construction of the low-field setup. The key components, including the superconducting magnet, SQUID, and the lock-in amplifier, are in operation. Preliminary measurements with a thermally-polarized (polarization $\approx 1.8 \times 10^{-7}$) $1\,\text{cm}^3$ liquid methanol sample have been performed, and first limits of $3 \times 10^{-2}\,\text{GeV}^{-1}$ have been placed in the ALP mass range $5.576\,741\,\text{neV/c}^2$ to $5.577\,733\,\text{neV/c}^2$. This narrow-bandwidth search served as a commissioning test and proof of principle for the methodology of CASPEr-Gradient.

Hyperpolarization of ^{129}Xe sample has been demonstrated with our setup, and a polarization on the order of 10 % was achieved. Currently we are constructing a transportation system between the polarizer setup and the magnets. We expect challenges with the stability of hyperpolarized ^{129}Xe production and efficient transportation without loss of polarization.

The construction of the high-field setup is almost finished. The superconducting magnet and devices for NMR experiments have been installed, and the first NMR spectrum has been acquired with the setup. Currently, the noise in the detection chain is being optimized.

For both low-field and high-field apparatuses, challenges are expected with ensuring reliable performance of the experiment in terms of an efficient duty cycle for ALP dark matter measurements.

3.2 GNOME

The GNOME collaboration has established a robust operational network of optical magnetometers with demonstrated sensitivity to spin-dependent couplings of ultralight bosonic fields. The network has successfully completed five Science Runs, during which extensive infrastructure for synchronization, environmental monitoring, glitch vetoing, and calibration has been developed and validated.

One key challenge is mitigating local magnetic noise and non-stationary backgrounds. This is addressed through multiple layers of shielding, regular injection of calibration pulses, and the use of auxiliary sensors (accelerometers, magnetometers, photodiodes, etc.) at each site to flag data affected by environmental perturbations. GPS-based time synchronization ensures nanosecond-level timing precision across the network.

The primary ongoing upgrade is the deployment of *Advanced GNOME* stations utilizing noble-gas–alkali-metal comagnetometers. These devices offer superior sensitivity—down to 10^{-21} eV/$\sqrt{\text{Hz}}$ for neutron spin couplings—while operating in a self-compensating regime that suppresses magnetic backgrounds. The implementation of these systems across multiple locations presents both technical and logistical challenges, including optimization of sensor stability, calibration consistency, and long-term autonomous operation.

A further challenge lies in the diversity of magnetometer technologies and species used across the network. While this diversity increases the network's reach in parameter space, it also necessitates careful modeling of each sensor's response to exotic spin couplings, particularly given the dependence on atomic and nuclear spin content.

On the data analysis side, one of the main difficulties is distinguishing rare transient exotic signals from noise events and systematic drifts. GNOME is actively developing data analysis frameworks, including matched filtering, spatiotemporal cross-correlation, and machine learning techniques for anomaly detection.

Finally, integrating GNOME with complementary observatories—such as atomic clock networks, gravitational wave detectors, and astrophysical triggers (e.g., black hole mergers or fast radio bursts) presents both an opportunity and a coordination challenge, particularly for real-time multimessenger data analysis.

3.3 GravNet

GravNet scientific goals will eventually require the design, optimization and construction of several microwave cavities and the establishment of data analysis tools and network techniques to maximize their combined data.

Current technology is already mature enough to build the cavities required for the first stages of GravNet. Still, the geometry of the optimal set of GHz cavities to be distributed around the different laboratories of Europe, their coating and the modes that will be read-out needs to be optimized during the next three years. This will require state-of-the-art simulations including GWs yet to be performed.

More open are the read-out techniques that may be eventually employed, and whose challenges are similar to those of other cavity experiments looking for photons. A key difference is that, given their possible transient and chirping nature, GWs may require a multimode tracking, for modes that individually have less than a single photon. Quantum sensing could be a game-changer in this multimode-sensing direction.

Another characteristic challenge relies on the techniques for coordinating the data of the several stations. This may require capacities at the limits of GNSS or other protocols, which is currently under study.

3.4 MAGO

An SRF cavity is required for this experiment so as to maximise the stored EM energy in the cavity. The large quality factor also helps in suppressing various anticipated sources of noise that ultimately limit the detector's sensitivity. A spherical 2-cell cavity (one of the old MAGO prototypes) is currently under investigation by the collaboration. An initial characterization and tuning of the cavity have been performed [105], along with surface treatment and cryogenic tests. In particular, the recent cryogenic tests indicate that the cavity meets the necessary criteria to be used for a first measurement. The short term goal is to do a proof-of-principle measurement with this cavity in an existing cryostat. This would represent the first direct probe of GWs in the targeted frequency range.

As the next step in advancing the technology, a dedicated experiment within existing cryostats is planned. This will facilitate the development of optimized cavities and to further enhance the LLRF system to drive and readout the cavity with strongly suppressed oscillator noise. Among the main challenges is to build a suspension system to reduce vibrational noise and a comprehensive understanding of the effects of submerging cavities in He-II.

In the longer term, scaled-up cavities housed in a dedicated ultra-low noise cryostat could significantly enhance sensitivity.

3.5 RADES

Counting photons at frequencies of ~ 10 GHz can be done by inducing anharmonicity in the microwave cavity mode in order to separate the energy levels (which would increase the distinguishability of the photon states) or by directly connecting the microwave cavity to a superconducting qubit single photon detector with a low dark count rate [9, 95]. As a reference, a benchmark axion model like KSVZ, predicts a photon occupation number of $\sim 10^{-5}$ in a cavity setup like the one of RADES, and this corresponds to a count rate of a few photons/s, which is a challenging requirement for the dark count rate, but it might be within reach given current technology. Indeed, to achieve these requirements, the scheme proposed in the RADES experiment relies on an anharmonic, ideally non dissipative, circuit element. One obvious candidate is a transmon-like qubit. The anharmonicity is a crucial resource for amplification. Thanks to its large electric dipole, a transmon qubit can be used to make single photon detectors [9, 95] both in the dispersive and the resonant regime. In both these regimes, the transmon is used as a non-linear coupler between two microwave cavities. In our case, we will use 3D cavities like in reference [9]. The main idea is that the presence or not of a photon impinging one the generation cavity can trigger a real or virtual transition between the ground state $|0\rangle$ and the first excited state $|1\rangle$. The generation cavity can be used as a storage cavity for the photons emitted by the inverse Primakoff process, like proposed in reference [9], or be the first element of the single photon detector to be connected to the cavities.

The dark count rate is determined by electromagnetic noise and by spurious heating effects of various origins - most notably backflowing infrared radiation from the HEMT amplifiers and cosmic radiation.

3.6 SRF Heterodyne

A technological demonstrator is funded by the Quantum Technology Initiative (QTI) at CERN, with involvement from the Physics Beyond Colliders (PBC) group. Design of the SRF cavity started in January 2025.

The foremost challenge lies in the design and optimisation of a suitable RF cavity and tuning system. The conceptual design of two superconducting RF cavities which satisfy these requirements is underway at CERN. In parallel, a novel means of non-mechanical tuning based on tuning stubs with controllable reactance is also under consideration at CERN, as a means to provide the required in-situ adjustment of the frequency spacing under cryogenic conditions.

To measure axion-induced excitations with a data acquisition (DAQ) system, various sources of noise are expected to limit the detection setup's sensitivity, and advancement of current RF measurement technology is paramount. To this end, advances in both front-end signal enhancement and back-end noise suppression offer improved sensitivity for axion search methods, with the feasibility of integrating quantum amplifier technology in the cryogenic environment in parallel with phase noise suppression algorithms in the DAQ under consideration by several research groups. Although the former technology is commonly employed in quantum information systems, challenges are anticipated in integrating it into the read-out chain of a noise suppressed RF cavity-based system. Prototyping of the such a readout chain within CERN's existing superconducting RF cavity DAQ systems is expected over the coming two years.

3.7 Theory

The theoretical work necessary to optimise experimental searches that go beyond the SQL is already underway. A study for axion dark matter is in progress, with straightforward extensions to other dark matter candidates. A study of quantum protocols for GW detection is also in progress.

An important challenge is the inclusion of realistic losses from experimental apparatus in theoretical estimates. For example, it is known that losses can impose a limit on the QFI of a detection scheme that does not saturate the quantum Cramer-Rao bound [106–110]. Since losses are dependent on the specific experimental implementation, theoretical results should be obtained that apply generally. This way, each experimental collaboration can determine the optimal approach for their detector, given their losses.

4 Timeline

4.1 CASPEr

The low-field setup of CASPEr-gradient has finished its first commissioning round of data taking, including data analysis, in 2024. Currently, the infrastructure for sample transport and insertion is being constructed, and a science run over the full accessible mass range with hyperpolarized xenon sample is planned within the year of 2025. In parallel, the high-field setup is performing commissioning measurements including calibrations, and is projected to conduct the first science run with hyperpolarized xenon sample by 2026. From 2026 onward, the goals of the collaboration are the development and testing of various hyperpolarization techniques, optimization of the setup, such as noise reduction, as well as further science runs with the upgraded setup and samples.

4.2 GNOME

The GNOME network has been operational since 2017 and has completed five coordinated Science Runs, each contributing to improved sensitivity, data quality, and analysis techniques. The current phase of the experiment focuses on upgrading existing stations and expanding the network with next-generation *Advanced GNOME* comagnetometers. The near-term timeline (2025–2026) includes full deployment of comagnetometers at key network sites, completion of the first Advanced GNOME Science Run, and continued refinement of cross-correlation and matched-filter analysis techniques for transient signal detection. From 2026 onward, the network will continue long-duration data taking and explore improvements to sensor stability, sensitivity, and bandwidth to broaden the BSM parameter space probed.

4.3 GravNet

GravNet started in March 2025, with the funds from an ERC Synergy grant. The period 2025-2028 will be devoted to the construction of the haloscopes with GHz cavities of Bonn, Mainz and Villigen, the adaptation of the QUAX@LNF GHz haloscope and the cosntruction of the 100 MHz haloscope FLASH both in Frascati. The analysis of existing data from other cavities is expected by 2025. The development of the networking capacities has already started and is scheduled to be finished by 2028.

The period from 2028 will consist of data taking periods and the expansion to new sites. It will also see the development of new read-out techniques (in particular close and beyond the SQL) to increase the sensitivity.

4.4 MAGO

A first proof-of-principle measurement with the MAGO cavity and a search for high-frequency GWs is expected by early 2026. A dedicated follow-up experiment, still using an existing cryostat but incorporating newly developed and improved cavities along with a suspension system, is projected to be fully functional approximately five years later.

4.5 RADES

RADES works on the development of the 3d transmon qubit detection system began in 2024 and the complete set-up is expected to be ready in the coming years.

4.6 SRF Heterodyne

Within the context of the CERN Quantum Technology Initiative, a dedicated five-year development of a SRF cavity based heterodyne demonstrator for axion searches was launched, starting in January 2025. The 2025-2027 period is dedicated to the design, construction and integration of a bespoke axion detection demonstrator which exploits the heterodyne principle. In parallel, existing cryogenic facilities at CERN are being repurposed to provide the experimental infrastructure, and dedicated DAQ systems are being investigated. Integration and system testing is foreseen for 2027 and the expectation of initial data-taking runs in 2028.

4.7 Theory

Fully general theoretical computations of quantum limits on axion DM detection should be available by Q1 2026. Equivalent results for other DM candidates should follow soon after. Full results for quantum limits on GW detection should also be available by Q1 2026.

5 Conclusion

In this report, we have summarised the ongoing and planned activities of a subset of European groups aiming to develop the theory and implementation of quantum sensors in the search for dark matter and gravitational waves. There are strong theoretical motivations for developing sensors capable of achieving sensitivity beyond the SQL. A handful of groups have already achieved some success in this area, but more is required. We have presented here the activities of CASPEr, GNOME, GravNet, MAGO, RADES, SRF Heterodyne and some theorists aiming to achieve beyond SQL sensitivity to dark matter and gravitational waves in the next few years.

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