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PAPER

Dark matter searches using accelerometer-based networks

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Abstract

Dark matter (DM) is one of the biggest open questions in physics today. It is known that it interacts gravitationally with luminous matter, so accelerometer-based searches are inherently interesting. In this article we present recent (and future) searches for DM candidates such as feebly interacting matter trapped inside the Earth, scalar-matter domain walls and axion quark nuggets, with accelerometer networks and give an outlook of how new atomic-interferometry-based accelerometer networks could support DM searches.
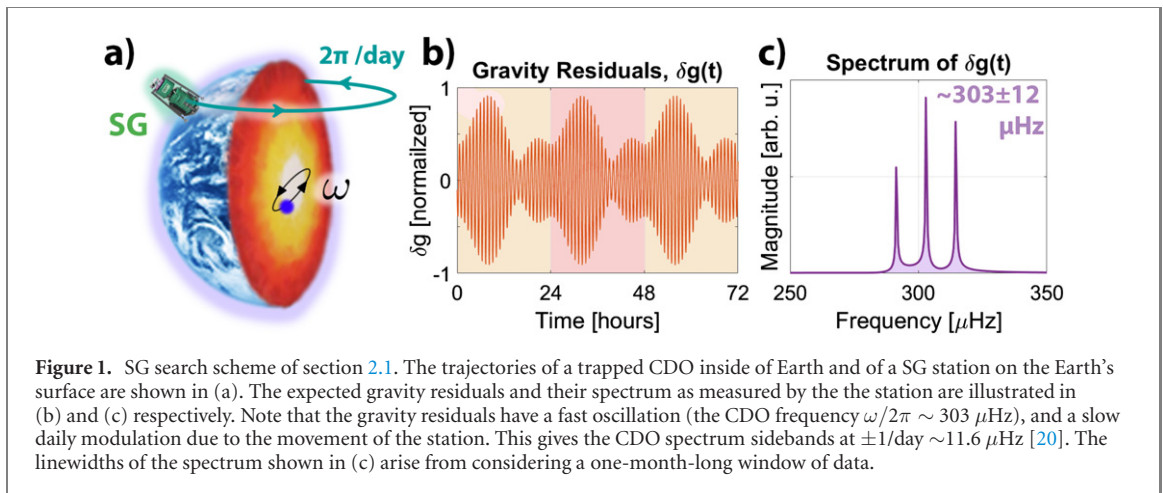
1. Introduction

After decades of research, the evidence for dark matter (DM) has become increasingly significant, indicating that $\sim$85% of gravitating matter in the Universe is nonluminous. The nature of DM is still unknown and is one of the greatest unsolved mysteries in physics to this day. DM observations to date have been astronomical, but there is abundant DM in our Galaxy, so Earth-bound DM-sensitive experiments should be feasible and could provide key insights into DM's nature and morphology.

It is known that DM interacts gravitationally, so gravity-based DM searches are inherently interesting. Additionally, certain well-motivated DM-particle candidates would generate forces on luminous matter through exotic interactions. Both cases would provide signatures suitable for accelerometer-based detection. This prospect is particularly interesting because networks of gravimeters and seismometers are already in place around Earth and have been collecting data for decades. In this article, we review recent searches for DM using these networks and explore how future searches might look like. Additionally, we discuss the development of accelerometers based on atom-interferometry and their potential use as a network to search for DM. Alternative gravity-based DM searches using lunar ranging (see reference [1] and references therein) are possible, as well as purely gravitational detection of individual DM particles, which was recently discussed in reference [2]; and also [3] in this special issue.

2. Superconducting gravimeters (SGs)

SGs [4, 5] are accelerometers that use superconductors to magnetically levitate a mass, effectively creating a stable spring-mass system. The position of the mass can be monitored and kept at a fixed position using feedback coils. This feedback signal is proportional to the displacement of the test mass, providing a practical method for measuring its acceleration. Such gravimeters have a high precision ($\sim$0.01 μGal; 1 μGal = 10 nm s^{-2}), small drift ($\sim\mu$Gal/year), and have been of great service to the study of a plethora of geophysical phenomena, as well as fundamental research, for example in the search for Lorentz violation in gravity [6].

The International Geodynamics and Earth Tide Service (IGETS) [7] provides long-term records of SG stations around Earth aiming to monitor the temporal variations of the gravitational field of the Earth to

Figure 1. SG search scheme of section 2.1. The trajectories of a trapped CDO inside of Earth and of a SG station on the Earth's surface are shown in (a). The expected gravity residuals and their spectrum as measured by the the station are illustrated in (b) and (c) respectively. Note that the gravity residuals have a fast oscillation (the CDO frequency $\omega/2\pi \sim 303\,\mu$Hz), and a slow daily modulation due to the movement of the station. This gives the CDO spectrum sidebands at ± 1/day $\sim 11.6\,\mu$Hz [20]. The linewidths of the spectrum shown in (c) arise from considering a one-month-long window of data.

support geophysical research. The IGETS is a continuation of the Global Geodynamics Project [8, 9] that began operations in 1997, and has amassed a large collection of data that are readily available.

Recently, the IGETS data were used to look for various kinds of DM structures [10–12]. Although these structures were not observed, useful constraints on their parameters were placed. In the following subsections we discuss the DM structures that were looked for, their expected signature and future possibilities of improved searches.

2.1. Compact DM object (CDO) search

This subsection is a summary of the work presented in references [10, 11].

Many DM models predict the formation of CDOs [13–16]. The CDOs considered here are assumed to have weak nongravitational interactions, and exclude black holes, as these would devour Earth. Limits for CDOs come from gravitational-lensing searches that have ruled out DM being made of CDOs with masses between 10^{-11} and 15 Sun masses, $M_\odot$ [17].
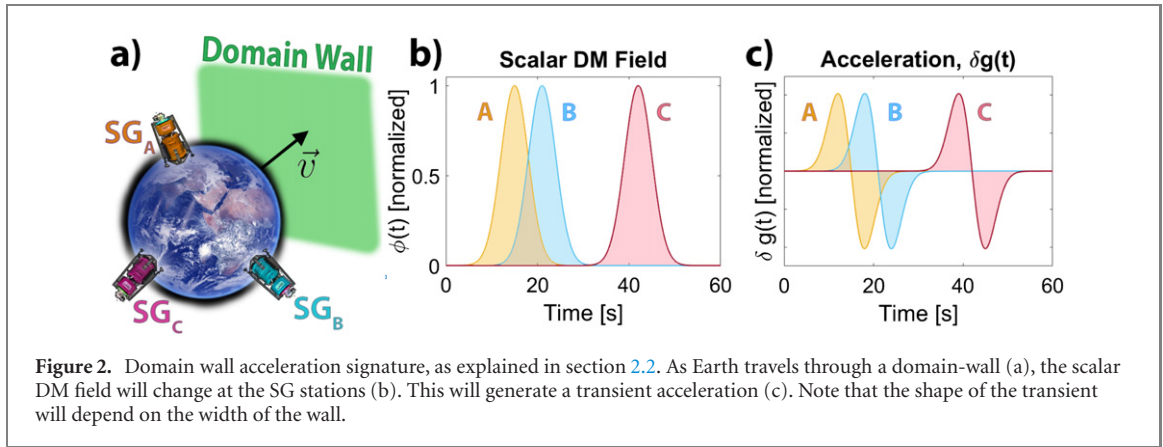
Throughout the lifetime of the Earth, a CDO could have been captured by the planet's gravitational well, through a three-body interaction or some other mechanism [18]. Once inside the Earth, the motion of the CDO would gradually dampen by weak nongravitational interactions and/or dynamical friction [19] (which is gravitational in nature), until the CDO's orbit is near the Earth's core (figure 1). Then, the orbits will have a well defined period of $2\pi/\omega \approx 55$ min, as the density of the Earth's core is uniform, and this frequency will be independent of the CDO's mass and the specific geometry of the orbit. A SG station on the surface of the Earth would experience acceleration due to (1) the direct gravitational attraction of the CDO and (2) the acceleration of the Earth toward the CDO, where these contributions, 1 and 2, are of the same order. The magnitude of the acceleration at the gravimeter station due to the CDO will be approximately

$$\delta g \approx \left(2 + \frac{\rho_{\rm c}}{\bar{\rho}}\right)\left(\frac{m}{M_\oplus}\right)\left(\frac{\ell}{R_\oplus}\right)g, \tag{1}$$

where $\bar{\rho}$ and $\rho_{\rm c}$ are the average densities of the Earth and the Earth's core, $M_\oplus$ and m are the masses of the Earth and the CDO, $R_\oplus$ and ℓ are the radii of the Earth and the CDO's orbital motion, and g is the gravitational acceleration due to the Earth. For a sense of scale, consider that for $m = 10^{-11}M_\oplus$ and $\ell = 0.1R_\oplus$, δg corresponds to 22 pm s^{-2}. Note that additional factors are needed to properly account for the dependence of δg on the position of the gravimeter with respect to the CDO orbit, a useful discussion regarding this can be found in the supplemental material of reference [10].

Because of the Earth's rotation, the spectrum of the CDO-induced acceleration at a gravimeter station will acquire sidebands at $\omega \pm (2\pi/\text{day})$. The ratios between the three relevant peak heights will depend on the specifics of the CDO orbit [20]. Additionally, inhomogeneities in the density of the Earth lead to higher harmonics in the spectrum, and although their contribution is negligible for oscillations near the center of the Earth, they become relevant for larger CDO amplitudes and could be useful for future searches.

A slightly different approach was taken by Hu and colleagues [11]. They extracted the residual gravity data from the IGETS network's level 3 data [21, 22], separated it into uninterrupted 1 month-long blocks and averaged their power spectral densities. No excess power was observed at the expected frequency ω, which allowed them to place limits at the $m < 1.3 \times 10^{-11}M_\oplus = 8 \times 10^{13}$ kg level (assuming an $\ell = 0.1R_\oplus$ orbit). Although more stations were involved in this analysis (providing a more uniform sensitivity across

Figure 2. Domain wall acceleration signature, as explained in section 2.2. As Earth travels through a domain-wall (a), the scalar DM field will change at the SG stations (b). This will generate a transient acceleration (c). Note that the shape of the transient will depend on the width of the wall.

the Earth), the limit is weaker due to the poor scaling of power averaging and the chopping of the data into 1 month-long blocks, which artificially broadens the spectrum of the CDO.

Future Earth-bound searches for CDOs could look into non-conventional CDO orbits, including those not trapped by the Earth but passing through it. Additionally, a more involved analysis of the entire data provided by the IGETS network could already provide an improvement on the current limits.

2.2. Domain-wall search

This subsection is a summary of the work presented in reference [12].

Axions are promising DM candidates, they were originally conceived to solve the strong-CP problem, and it was later found that they could also account for the DM content of the Universe. Axions and other ultralight (masses between 10^{-22} and 1 eV [23]) DM fields might form spatially inhomogeneous structures that could be arranged in 2D (sheet-like), 1D (line-like) and 0D (point-like) configurations.

As the Earth moves in the galaxy, it would travel through these structures. Furthermore, if we assume that the DM field couples with scalar couplings to luminous matter, traveling through these structures could effectively cause an apparent shifting of fundamental constants. This could lead to a change in the mass of fundamental particles. In particular, for a quadratic coupling, the effective mass of fermions will be given by

$$m_f^* = m_f \left(1 + \Gamma_f \phi(r, t)^2 \right), \tag{2}$$

where m_f refers to fermion mass, where the fermion could be electron, proton, or neutron; Γ_f is the corresponding coupling constant, and ϕ is the DM field.

The change of mass of fundamental particles would change the mass of everything in the planet. While a consistent dynamic theory describing the scalar DM interaction with luminous matter is still under development [24], in a naive picture this would lead to a detectable acceleration through the following mechanism: the energy of particles on Earth will be dominated by their rest mass, $E \sim mc^2$, and the coupling described in equation (2) will give mass a spatial dependence. So there will be a force due to the gradient of the energy $\vec{F} = -\vec{\nabla} E$, leading to a corresponding acceleration given by
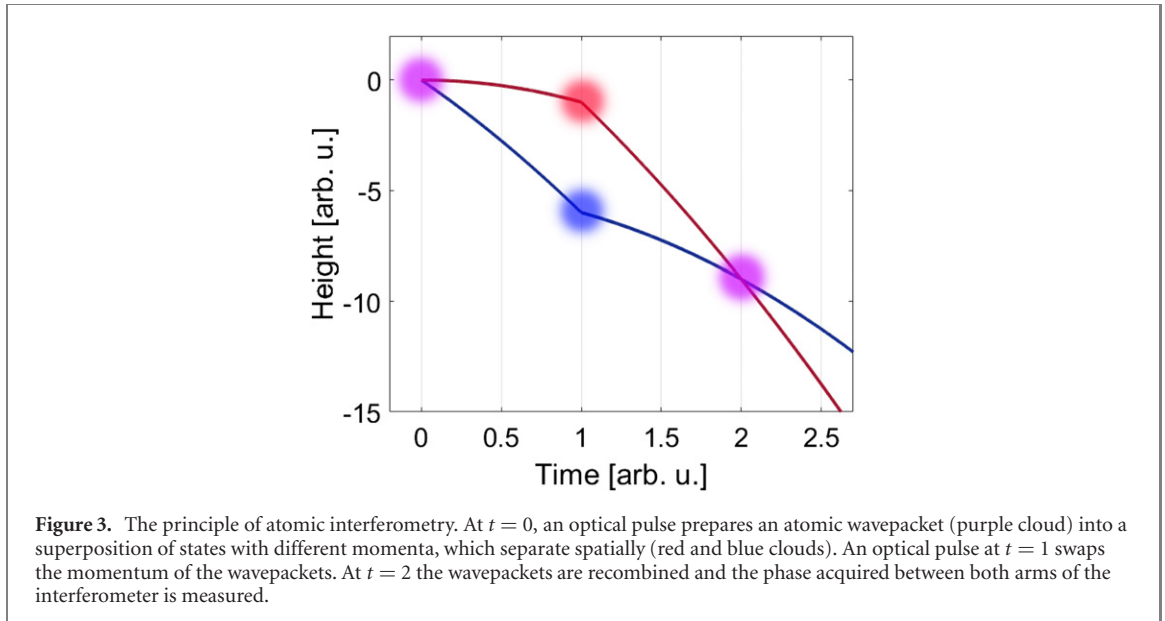
$$\vec{a} = \frac{1}{m^*(r, t)} \left[-\vec{\nabla} \left(m^*(r, t) c^2 \right) \right]. \tag{3}$$

This acceleration transient will affect the test mass in SGs, providing a direct approach for a domain wall search, as illustrated in figure 2.

In a recent article by McNally and Zelevinsky [12], the authors estimated the sensitivity of the IGETS network to such transient events (for 2D sheet-like structures), and showed that such a search could look for a wide range of structure sizes spanning from 10^{-5} to 10^8 km. In the case of non-detection, such a search could provide the strongest limits on the coupling constants to date, currently held by a GPS-clock-based search [25].

3. Atom interferometry based sensors and networks

Since the famous experiments [26] exploiting neutrons, one of the most fascinating applications of matter-wave interferometry is probing gravity. The driving force for advancing these interferometers is more stringent and complementary tests of special and general relativistic effects, detecting infrasound gravitational waves and the search for DM and dark energy [27–31]. Moreover, next to fundamental

Figure 3. The principle of atomic interferometry. At $t = 0$, an optical pulse prepares an atomic wavepacket (purple cloud) into a superposition of states with different momenta, which separate spatially (red and blue clouds). An optical pulse at $t = 1$ swaps the momentum of the wavepackets. At $t = 2$ the wavepackets are recombined and the phase acquired between both arms of the interferometer is measured.

research, applications of matter wave interferometers range from navigation to geophysics and geodesy, for example for monitoring mass-transport phenomena in hydrology or volcanic research. Mass-transport phenomena occur at a wide range of frequencies and include diurnal periods as well as slow processes such as the post-glacial landlift, to mention an extreme case.
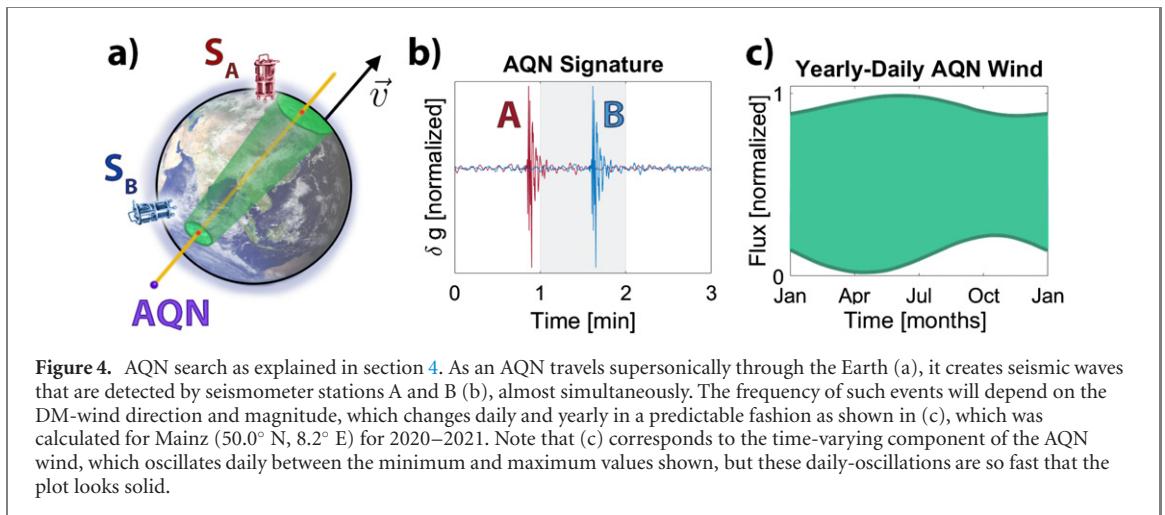
Light-pulse atom interferometry [32] is the most common method employed for those measurements including those done with commercial instruments (figure 3). Light-pulse interferometers belong to the class of absolute gravimeters without need for calibration. They have shown convincing performance with respect to the measurement sensitivity at low frequencies, long-term stability and accuracy. Moreover, light-pulse interferometry offers high flexibility in creating instruments with a wide range of topologies that can measure different quantities like inertial forces, gradients [33] and curvatures, with a single device.

The most basic type of interferometer, called Mach–Zehnder interferometer in analogy with optics, measures accelerations acting on matter waves during their free fall. The interferometer is created by driving optical, Raman or Bragg processes in the matter wave by stationary or running optical lattices such that the matter wave is coherently split, deflected and recombined by three successive light pulses ideally resulting in two outputs with complementary interference fringes. The optical lattice is created out of a light wave being reflected off of a mirror serving as inertial reference and connecting the measurement to the laboratory system. The phase depends on the double differential of the atomic motion between the third and the second and the second and the first light pulses. Hence, in the case of a spatially uniform force and constant lattice, the phase ϕ is determined by the acceleration g, the square of the time T the atoms spend between the light pulses and the relative momentum k of the split matter waves which is proportional to the photon recoil of the corresponding lattice,

$$\phi = \vec{k} \cdot \vec{g}\, T^2. \tag{4}$$

Starting with the famous Kasevich–Chu interferometer [32, 34], a large number of such devices were developed around the world since the nineties, especially to measure gravity. These interferometers are presently commercialized by several companies as gravimeters. Currently, the best measurements reach an accuracy of 32 nm s^{-2} [35] and show long-term instabilities of 0.5 nm s^{-2}, necessitating SGs for verification [36] of the instrument-related instabilities. The use of ultracold atomic ensembles, e.g. those created by evaporative cooling [37] or even Bose–Einstein condensates [38], promises to improve the results by more than an order of magnitude.

Extending the time of free fall between the light pulses as well as the momentum transferred by the lattice allows to enhance the sensitivity of the interferometer. This motivated current activities building large light-pulse interferometers as pioneered at Stanford [39]. Moreover, in the context of gravitational wave detection, pairs of such interferometers interacting with the same optical lattice, are under construction forming highly sensitive gravity gradiometers. Most recently, within this device, a quantum test of the equivalence principle, comparing the relative motion of atomic ensembles comprising ^{85}Rb and ^{87}Rb has been achieving a sensitivity for differential accelerations of 10^{-12} of the Earth gravity [40], improving on previous experiments [41, 42]. Other isotope-pairs that have also been used to measure differential accelerations are ^{39}K with ^{87}Rb [43], and ^{88}Sr with ^{87}Sr [44].

Figure 4. AQN search as explained in section 4. As an AQN travels supersonically through the Earth (a), it creates seismic waves that are detected by seismometer stations A and B (b), almost simultaneously. The frequency of such events will depend on the DM-wind direction and magnitude, which changes daily and yearly in a predictable fashion as shown in (c), which was calculated for Mainz (50.0° N, 8.2° E) for 2020−2021. Note that (c) corresponds to the time-varying component of the AQN wind, which oscillates daily between the minimum and maximum values shown, but these daily-oscillations are so fast that the plot looks solid.

Individual atomic interferometers are already sensitive to ultralight DM [45–47]; but a global network of such sensors could be used to search for DM structures on a larger sale, such as the domain walls described in the previous section. This is an exciting prospect, given that today there are several activities around the world constructing very-long-baseline in Australia [48], China [49], and in the US [50], as well as gradiometers, where atom interferometers are compared with a common lattice beam covering large distances. These devices will range in size from ∼10 m to ∼100 m with future plans to reach 1000 m in some cases, and are being constructed in China (ZAIGA) [51], France (MIGA) [52], and the US (MAGIS) [53] or are planned such as the AION [54] or the European large facility (ELGAR) [55].

These atomic interferometers would be sensitive to the class of DM described in the previous section; if there is a different DM coupling to protons and neutrons, it would appear as a differential gravitational acceleration dependent on the proton/neutron ratio of different isotopes. A network of atomic interferometers could be used to look for the domain walls discussed above.

In addition, experiments in space are proposed for testing fundamental physics. Most recently, in the context of ESA's call for mission ideas for the Voyage 2050 program, several experiments based on atom interferometers were proposed to perform a quantum test of the equivalence principle, for detection of gravitational waves, and to search for DM. We note that a comprehensive review of atom interferometry and its utility for DM searches by Tino can be found in reference [27] in this special issue.

4. Axion antiquark nugget (AQN) seismology

An intriguing possibility is that axion domain walls are not long-lived, and collapse during the QCD transition in the early universe. Domain walls could exhibit substructure at the QCD scale that would prevent fermions from easily crossing them. The collapse of bubble-shaped domain walls would compress the (anti)quarks inside them into a dense state, until an equilibrium is reached when the Fermi pressure of the trapped (anti)quarks counters the squeezing caused by the collapsing domain wall. The pressure exerted by the domain wall could be such that the internal (anti)quarks enter the color-superconducting phase, which would make the system stable, as the mass of these composite objects-known as (anti)quark nuggets-would be smaller than that of their free separated components [56].

(Anti)quark nuggets are a compelling DM candidate. Their origin is the same as that of luminous matter (baryons), so they would naturally occur in a comparable abundance without the need of finely-tuned parameters, explaining why we have comparable amounts of dark and luminous matter. Additionally, an excess of axion antiquark nuggets (AQNs) over axion quark nuggets can explain the observed matter to antimatter excess in the Universe: matter and antimatter could have been created in the same amount, so the total baryon charge of the Universe would be zero at all times, but more antimatter could be trapped inside nuggets (in contrast to the conventional baryogenesis paradigm where more matter than antimatter was produced in the early Universe). The excess of anti-nuggets to nuggets could arise from strong CP violation in the QCD epoch.

Furthermore, (anti)quark nuggets have been proposed as an explanation for a wide variety of open questions in physics such as: the primordial lithium puzzle [57], the anomalous temperature of the solar corona [58], the creation of small craters that are not attributed to meteorites [59], some astronomical x-ray emissions [60], and skyquakes [61] which have been routinely observed on Earth.

DM made of (anti)quark nuggets could interact with luminous matter but would remain cosmologically dark due the small cross-section-to-mass ratio of the nuggets. AQNs are particularly reactive, and as they travel through luminous matter, part of the AQN contents would annihilate with the medium and emit x-ray photons. If this were to happen inside the Earth, the released energy would generate a seismic signature that could be looked for with seismometers. It should be noted that seismic searches looking for related DM candidates [62, 63] have been already carried out in the Earth [64] and Moon [65].

The seismic signature of an AQN would have properties that would make it discernible from run-of-the-mill earthquakes. Assuming that AQNs are virialized [66] their velocity in the galactic frame along each of the Cartesian coordinates would be distributed as a Gaussian centered at zero, with a dispersion of $\sigma \sim 110$ km s^{-1}. As the Earth moves with a velocity of $\sim$220 km s^{-1} through this AQN-gas, the AQN impacts would come from a preferential direction, and with a mean velocity of $\sim$220 km s^{-1} [67]; the time-varying component of this AQN-wind is shown in figure 4(c). It should be noted that, due to the AQNs virialized nature, a constant flux of AQNs of comparable magnitude is also expected.

As an AQN travels through the Earth at a supersonic velocity, it generates acoustic waves with a conical, almost cylindrical wavefront (figure 4). It also creates surface waves at the points of entry and exit, which would seem to appear nearly simultaneously (within $\sim$1 min) on opposing sides of the Earth. Furthermore, the preferred direction and frequency of AQN events would have a daily and yearly modulation due to the rotation and motion of the Earth, providing yet another feature that would be exclusive to AQN-produced earthquakes. AQN events would also emit axions [67, 68] that could, in principle, be detected by other networks (but that is a much harder task than detecting sound, as axions would couple weakly to luminous matter).

The sensitivity of a seismometer network to AQN events depends on the search strategy. Designing a promising search strategy is not trivial, especially considering that some noise sources observed by seismometers exhibit daily and yearly modulation of their own [69]. Additionally, a proper model for the AQN acoustic generation mechanism must be developed that would consider the complexities of acoustic propagation through the Earth. An ongoing effort is focused on simulating the seismic signature of an AQN event that would inform a search using a seismometer network the near future. Such a search might be able to probe an unexplored range of the free parameter of the AQN model, the average baryon charge in the nuggets, $\langle B \rangle$. Preliminary results from these simulations [70] suggest that an AQN with $\langle B \rangle \sim 10^{25}$ could produce a displacement-wave of several nanometers in the vicinity of 10 s of meters in solid granite, which could be within the detection capabilities of modern seismometers. Larger AQNs would produce bigger displacements, but also occur at a lower rate.

Current constraints on $\langle B \rangle$ come from the IceCube Observatory (see appendix A in reference [67]), placing a limit of $3 \times 10^{24} < \langle B \rangle$ and from a reinterpretation [61] of the search using the Apollo data mentioned earlier [65], giving $\langle B \rangle < 10^{28}$. Together, they leave an unexplored window $3 \times 10^{24} < \langle B \rangle < 10^{28}$, which could be investigated with a seismometer-network.

5. Conclusion

DM detection based on the existing and emerging gravimeters and seismometers, while being somewhat 'on the fringe' of DM searches is nevertheless gaining momentum, with good prospects for improved sensitivity and a reach across a broad range of DM models, from ultralight scalar fields to ANQs. With a broad network of DM detectors pushing technological limits, there are good chances of uncovering the nature and composition of DM in the near future.

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Data availability statement

No new data were created or analysed in this study.

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