Topical White Paper for 2023-2032 Decadal Survey

AEDGE:
Atomic Experiment for Dark Matter and Gravity Exploration in Space

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ABSTRACT: We present a concept for a space experiment called AEDGE using cold atom interferometry to search for ultralight dark matter (ULDM) and gravitational waves (GWs) in the frequency range between LISA and terrestrial laser interferometers. We illustrate AEDGE's sensitivity to ULDM and how its GW measurements could explore the assembly of super-massive black holes, first-order phase transitions in the early Universe and cosmic strings. AEDGE will build upon terrestrial cold atom experiments and benefit from the space experience obtained with LISA and cold atom experiments in microgravity.

The AEDGE concept [1] has been presented at the Workshop on Atomic Experiments for Dark Matter and Gravity Exploration held at CERN [2], was submitted to the ESA Voyage 2050 call for mission proposals [3], and discussed at a virtual Community Workshop on Cold Atoms in Space supported by the CERN Quantum Technology Initiative [4].

1 Science Case

Two of the most important issues in fundamental physics, astrophysics, and cosmology are the nature of dark matter (DM) and the exploration of the gravitational wave (GW) spectrum.

Multiple observations from the dynamics of galaxies and clusters to the spectrum of the cosmological microwave background (CMB) radiation indicate that there is far more DM than conventional matter in the Universe, but its physical composition remains a complete mystery. The two most popular classes of DM scenario invoke either coherent waves of ultra-light bosonic fields, or weakly-interacting massive particles (WIMPs). In the absence so far of any positive indications for WIMPs from accelerator and other laboratory experiments, there is increasing interest in ultra-light bosonic candidates, many of which appear in theories that address other problems in fundamental physics. *Such bosons are among the priority targets for AEDGE.*

The discovery of GWs by the LIGO [7] and Virgo [8] laser interferometer experiments has opened a new window on the Universe, through which waves over a wide range of frequencies can provide new information about high-energy astrophysics and cosmology. Just as astronomical observations at different wavelengths provide complementary information about electromagnetic sources, measurements of GWs in different frequency bands are complementary and synergistic. In addition to the ongoing LIGO and Virgo experiments at relatively high frequencies $\gtrsim 10$ Hz, which will soon be joined by the KAGRA [9] detector in Japan and the project [10] to build a LIGO detector in India, with the Einstein Telescope (ET) [11, 12] and Cosmic Explorer (CE) [13] experiments being planned for similar frequency ranges. In addition the space-borne laser interferometer experiment LISA [14], which will be most sensitive at frequencies $\lesssim 10^{-1}$ Hz, has been approved, and the analogous Taiji [15] and TianQin [16] missions are under consideration in China. AEDGE is optimized for the mid-frequency range between LISA/Taiji/TianQin and LIGO/Virgo/KAGRA/INDIGO/ET/CE [1]. This range is ideal for probing the formation of the supermassive black holes known to be present in many galaxies. Also, AEDGE's observations of astrophysical sources will complement those by other GW experiments at lower and higher frequencies, completing sets of measurements from inspiral to merger and ringdown, yielding important synergies as we illustrate below. GW measurements with AEDGE can also yield important insights into fundamental physics, as we also illustrate. *GWs are the other priority targets for AEDGE.*

In addition to these primary scientific objectives, several other potential objectives for cold atom experiments in space are under study. These may include constraining possible variations in fundamental constants, probing dark energy, and probing basic physical principles such as Lorentz invariance and quantum mechanics. Cold quantum gases provide powerful technologies that are already mature for the AEDGE goals, while also developing rapidly [22]. The developments of these technologies can be expected to offer AEDGE more possibilities in the coming years *AEDGE is a uniquely interdisciplinary and versatile mission.*

2 Experimental Considerations

The design of AEDGE requires two satellites operating along a single line-of-sight and separated by a long distance. The payload of each satellite will consist of cold atom technology as developed for state-of-the-art atom interferometry and atomic clocks. *As two satellites are needed to accomplish*

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[1] The ALIA proposal in Europe [17] and the DECIGO proposal in Japan [18] have been aimed at a similar frequency range, and the scientific interest of this frequency range has recently been stressed in [19, 20] and [21].

the AEDGE science goals, and in view of the international interest in these goals, we envisage the possibility of international cooperation and co-funding of the mission as for LISA.

There are several cold atom projects based on various technologies that are currently under construction, planned, or proposed, which address the principal technical challenges and could be considered in a detailed design for a mission proposal and corresponding satellite payload. For the option presented in the White Paper we choose to base our discussion on the concept outlined in [23–26], which is currently the most advanced design for a space mission. This concept links clouds of cold atomic strontium in a pair of satellites in medium-Earth orbit via pulsed continuous-wave lasers that induce the 698 nm atomic clock transition, and detect momentum transfers from the electromagnetic field to the strontium atoms, which act as test masses in a double atom interferometer scheme.

3 Technological Readiness

AEDGE will benefit from the experience gained with LISA Pathfinder in free-fall control and LISA itself in operating laser interferometers over large distances. We have identified the following three additional high-level technical requirements that are critical for AEDGE:

- Demonstrate reliable functioning of atom interferometry on a large terrestrial scale $\gtrsim$ 100m;
- Demonstrate that the design parameters assumed here, such as the large momentum transfer (LMT) enhancement, phase noise control, interrogation time, etc., can be achieved;
- Demonstrate the robustness of cold atom technology in the space environment.

Several terrestrial atom interferometer projects that would serve as demonstrators for different technologies are under construction, planned, or proposed.

These include three large-scale prototype projects at the 100-m scale that are funded and currently under construction, namely MAGIS-100 in the US [25], MIGA in France [27], ZAIGA in China [28], and now the first stage of AION in the UK [29], and there are projects to build one or several more km-scale detectors in the US (at the Sanford Underground Research facility, SURF), in Europe (MAGIA-advanced [30, 31], ELGAR [32]) and in China (advanced ZAIGA) that would serve as the ultimate technology readiness demonstrators for AEDGE. In parallel to these large-scale prototype projects, several other cold atom projects are in progress or planned, demonstrating the general readiness of the technology including the scaling of the basic parameters that are required for AEDGE.

Moreover, several cold atom experiments (CACES [33], MAIUS [34], CAL [35]) and underlying optical key technologies (FOKUS [36], KALEXUS [37], JOKARUS [38]) have already demonstrated reliable operation in space, and much more experience will be gained in the coming years.

In addition there are ongoing NASA, Chinese, ESA, German and French projects to conduct cold atom experiments in space, some of which have already provided operational experience with cold atoms in space or microgravity environments. These include the Cold Atom Laboratory (CAL) experiment on the ISS [39], the Chinese Atomic Clock Ensemble in Space (CACES) that has demonstrated in-orbit operation of an atomic clock based on laser-cooled rubidium atoms [33], the Atomic Clock Ensemble in Space (ACES/PHARAO) project that plans to install ultra-stable atomic cesium clocks on the ISS [40, 41], the Bose-Einstein Condensate and Cold Atom Laboratory (BECCAL) project [42], the ICE experiment that recently reported the all-optical formation of a BEC in the microgravity environment obtained on an Einstein elevator [43], and the ISS Space Optical Clock (I-SOC) project of ESA [44, 45] to use cold strontium atoms in space to compare and synchronize atomic clocks worldwide.

Other proposals for atomic experiments in space to probe fundamental physics include STE-QUEST [46], the Space Atomic Gravity Explorer (SAGE) mission [26], the SagnAc interferometer for

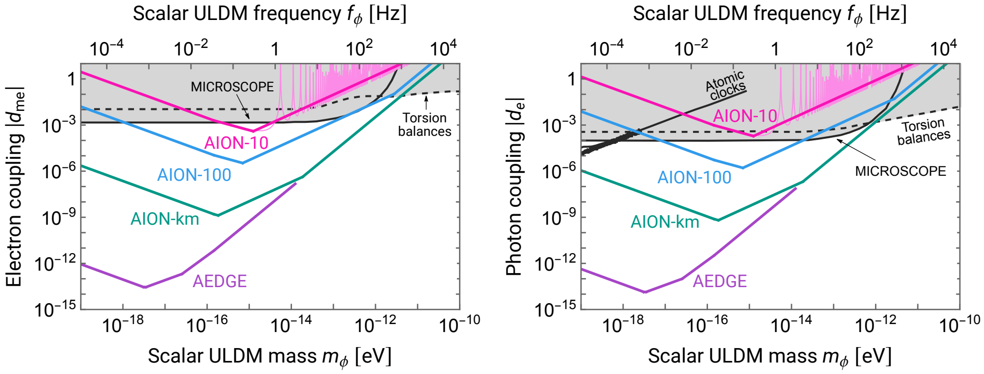

Figure 1. *Sensitivity projections to ultralight scalar dark matter coupled linearly to electrons (left panel) and photons (right panel). The lighter-pink AION-10 curve shows the oscillatory nature of the sensitivity projections, while the darker-pink straight AION-10 curve shows the envelope of the oscillations. For clarity, we only show the envelopes for AION-100, AION-km and AEDGE. The shaded grey region shows the existing constraints from searches for violations of the equivalence principle with torsion balances [49], atomic spectroscopy [50] and the MICROSCOPE experiment [51].*

Gravitational wavE proposal (also called SAGE) [47] and the Atomic Interferometric Gravitational-Wave Space Observatory (AIGSO) proposed in China [48].

4 Illustrative Science Capabilities

As already mentioned, the nature of dark matter is one of the most important and pressing in particle physics and cosmology, and one of the favoured possibilities is that it is provided by coherent waves of some ultra-light boson. We see in Fig. 1 that AEDGE will be able to explore large ranges of the parameter spaces of such models, complementing the capabilities of other experiments.

Experience with electromagnetic waves shows the advantages of making astronomical observations in a range of different frequencies, and the same is expected to hold in the era of gravitational astronomy. AEDGE would be ideal for exploiting the scientific opportunities in the mid-frequency band, complementing other experiments and offering synergies with them. Fig. 2 illustrates the capabilities of AEDGE for studies of black hole mergers, comparing the sensitivity of AEDGE with those of other operating, planned and proposed experiments, and Fig. 3 illustrates the capabilities of AEDGE for probing fundamental physics via gravitational waves from a first-order phase transition (left panel) and from cosmic strings (right panel).

Other possible opportunities for AEDGE in fundamental physics, astrophysics, and cosmology have been identified, but not yet explored in detail.

These examples show that AEDGE is a uniquely interdisciplinary mission that will harness cold atom technologies to address key issues in fundamental physics, astrophysics and cosmology. The worldwide spread of the authors of [1] indicate that there could be global interest in participating in this mission.

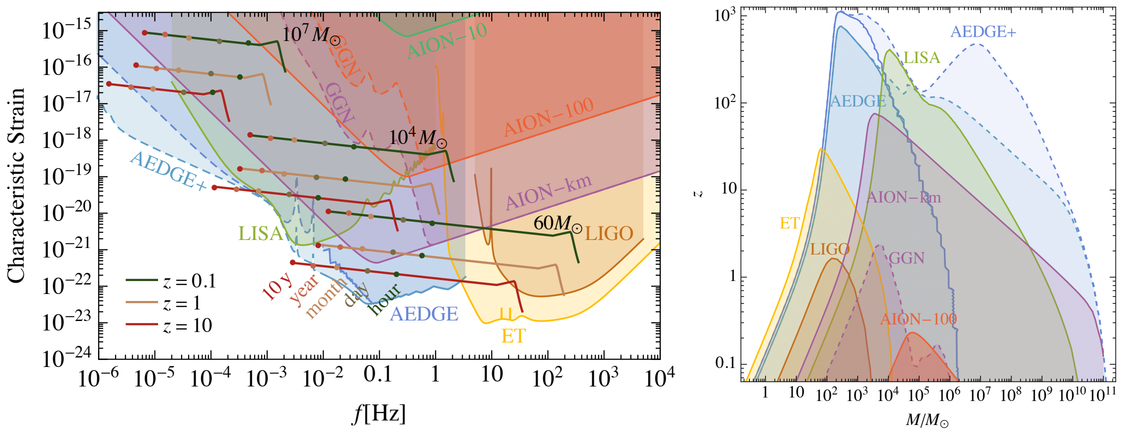

Figure 2. *Left panel: Strain sensitivities of AION-10, -100 and -km, AEDGE and AEDGE+, compared with those of LIGO, LISA and ET and the signals expected from mergers of equal-mass binaries whose masses are* $60, 10^4$ *and* 10^7 *solar masses. The assumed redshifts are* $z = 0.1, 1$ *and* 10, *as indicated. Also shown are the remaining times during inspiral before the final mergers. Right panel: Signal-to-noise ratio (SNR) = 8 sensitivities of LIGO, ET, LISA, AION and AEDGE to equal-mass black hole binaries as functions of the binary total mass and the redshift* z.

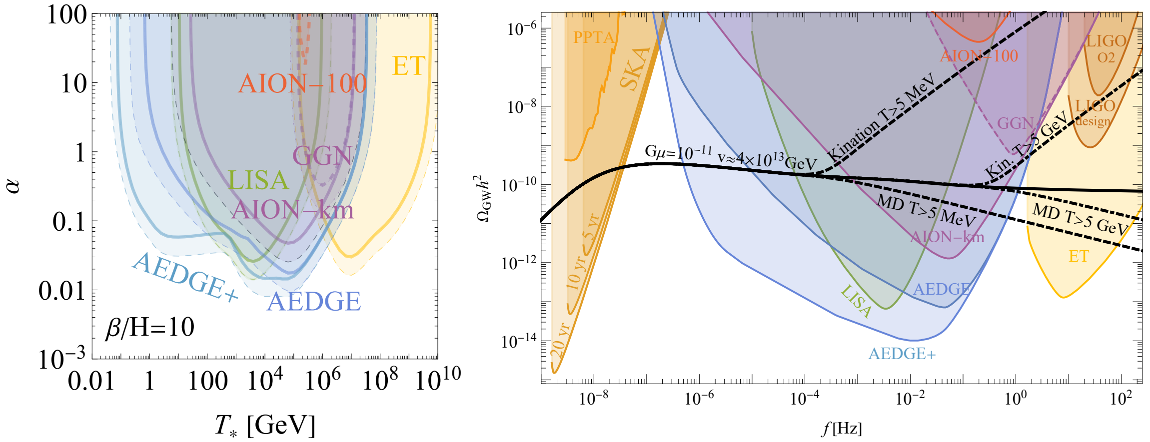

Figure 3. *Left panel: Sensitivities of AION-100 and -km, AEDGE and AEDGE+ and LISA in the* (T_*, α) *plane to GWs from generic first-order transitions with the transition rate* $\beta/H = 10$. *The thick solid lines are for* $SNR = 10$, *while the dashed lines are for* $SNR = 1$, *except for AION-km GGN for which the thick dashed line is for* $SNR = 10$ *while the dotted line is for* $SNR = 1$. *Right panel: Comparison of the sensitivities of AEDGE and other experiments to cosmic strings, illustrating the possible effects of kination or matter dominance (MD) at temperatures* $T > 5$ *MeV or* 5 *GeV.*

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