Snowmass2021 - Letter of Interest

Using gravitational-wave interferometers as particle detectors to directly probe the existence of dark matter

Thematic Areas: (check all that apply ☐/■)

■ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (Other) Theory Frontier, (TF09) Astro-particle physics & cosmology

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Abstract: (maximum 200 words)

Ultralight bosonic particles, well motivated by new physics beyond the standard model, can play the role of dark matter. These particles could interact directly with gravitational-wave detectors, and produce signals that would look similar to, but still distinct from, continuous monochromatic gravitational-wave signals, from e.g. asymmetrically rotating neutron stars or from depleting boson clouds around black holes. Using the last few years of LIGO-Virgo data, interesting constraints have been placed on both the degree of deformation on neutron stars, and possible boson/ black hole mass combinations. However, very little analysis has been done regarding direct dark matter detection through its coupling with the LIGO-Virgo interferometers. The use of the gravitational-wave antennas as dark matter laboratories is the beginning of a great synergy between the high-energy and gravitational-wave communities, and is a unique probe of dark matter physics.

Motivation. Ultralight bosons are promising dark matter (DM) candidates. For example, the QCD axion [1–4] naturally appears as a pseudo Nambu-Goldstone boson of a spontaneous global $U(1)$ symmetry. The dilaton, which naturally appears in extra dimension models, can also be light. Such scalar particles can be produced in the early universe and play the role of DM [5–10], with possible masses that span many orders of magnitudes [11]. The dark photon, a spin-1 particle, is also an strong candidate for dark matter, and could arise from the misalignment mechanism [12–14], parametric resonance or the tachyonic instability of a scalar field [15–18], or from cosmic string network decays [19]. Various experiments have been proposed to test the existence of ultralight DM particles, e.g. [20, 21], based on different hypotheses of DM interactions with standard model particles [22, 23]. However, in our case, a universal search strategy may be applied to GW detector data and provide access to several ultralight DM models simultaneously.

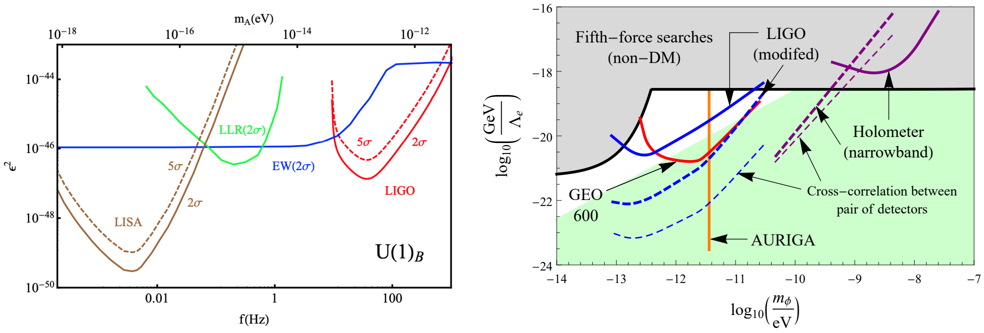
The LIGO-Virgo-GEO-KAGRA antennas [24–27] are very sensitive to small changes in distance. If ultralight particles compose DM, the detectors are embedded in the background of the DM field. Such a field would couple in a specific way to the interferometer components, causing a periodic movement [28] or length variation [29] of the mirrors. The de Broglie wavelength of the ultralight DM particles is typically much larger than the detector separation [30], meaning that all mirrors should experience almost the same force or variation, which leads to correlated signals among detectors. Additionally, because the mass of the particle is fixed, the signal is monochromatic, up to small variations related to the virial velocity of dark matter, which allows continuous gravitational-wave (CW) techniques to be readily applied.

The modeling of the ultralight dark matter background is straightforward [30]. Assuming a small mass and the local DM energy density, i.e. $\sim 0.4\ \mathrm{GeV/cm^3}$, a significant number of DM particle wavefunctions, approximately plane waves, overlap. The DM background is therefore described by a superposition of these plane waves, each with its own velocity that is governed by a Maxwell-Boltzmann distribution, with a peak at the virial velocity, $v_0/c = \mathcal{O}(10^{-3})$. Thus the broadening of the frequency is of $\mathcal{O}(10^{-6})$, even smaller than the Doppler shift considered in CW searches caused by the source's and earth's relative motion [31].

Different species of DM may couple differently to the standard-model sector and thus affect the interferometer components in unique ways. For example, dilaton-like scalar DM may induce apparent oscillations in the fundamental constants, such as the electromagnetic fine-structure constant α or the electron's mass [10, 32, 33]. Such non-gravitational interactions can affect the differential optical path length in a laser interferometer due to oscillations in the sizes of freely-suspended interferometer components, most importantly the beam-splitter and mirrors [29], via oscillating changes in the atomic Bohr radius [32, 34]. Meanwhile, dark photon DM may couple directly to the baryons in the mirrors of the interferometer cavities themselves, which causes the mirrors at different locations to feel slightly different forces [28, 35]. Also, axions may cause modulations in circular polarized photons' velocities, leading to a differential strain [36, 37]. Other interesting ideas to detect different kinds of dark matter with GW detectors exist as well [38–41].

Methods and searches Recently there has been a growing interest in developing or adapting methods to probe the existence of dark matter directly with the advanced gravitational-wave (GW) detector network. One example is the adaption of a cross-correlation technique [28] that has been historically used to search for stochastic GW backgrounds and CW signals. Figure 1a shows the potential of using LIGO-Virgo and LISA at their design sensitivities to deduce the coupling ϵ^2 of dark photons to baryons at the 2σ exclusion limit and 5σ discovery potential. The bounds that GW detectors can set are competitive with those from existing experiments, and do not require any modifications to the detector hardware.

Given the potential to see dark photons with GW detectors, the first search ever was performed using the cross-correlation technique on data from LIGO's first observing run for dark photons [42], resulting in interesting constraints on dark photon/baryon coupling. This search was computationally cheap, meaning that statements about particle physics can be made with very little investment in additional resources.



(a) Dark photon possible constraints

(b) Potential sensitivity to scalar-field dark matter

Figure 1: (Fig. 1 in [28] and Fig. 3(d) in [29].) The plots show the potential sensitivities to the underlying interaction parameters, as functions of the dark matter particle mass, for the vector (left plot) and scalar (right plot) cases, On the left, the curves corresponding to 2σ exclusion limits and the 5σ discovery potential are shown for LIGO and LISA for the dark photon coupling to the baryons in the mirrors for an observation time of two years. On the right, the projected sensitivities of LIGO, GEO600 and the Fermilab holometer to the scalar interaction with the electron are presented for three years of observation time.

In addition to a cross-correlation based search, the adaption of a semi-coherent technique used for an all-sky search for boson clouds around black holes [43] is in development to search for dark photons. The method relies on creating a collection of Fast Fourier Transform (FFT) databases assuming some frequency wandering in the signal expected from a boson cloud. Depending on how large this wandering is assumed to be, the maximum FFT duration changes. In the case of dark photons, the maximum FFT is a function of the virial velocity and the particle mass. Moreover, the CW follow-up techniques, the ways in which we confirm or rule out possible candidate signals, can be applied in the case of dark photon searches, but need to be done in slightly different ways, tuned to the specific signal morphology.

Though no searches for scalar DM using laser-interferometric GW detectors have yet been published (an analysis of GEO 600 data for this purpose is currently ongoing), it is possible to estimate their sensitivities to oscillations in the fundamental constants. Figure 1b shows the projected sensitivities of the existing LIGO and GEO600 interferometers, as well as the smaller-scale Fermilab holometer, to the interaction of scalar DM with the electron (analogous plots for the interactions of scalar DM with the electromagnetic field and nucleons are presented in [29]). Curves for modified versions of these interferometers are also shown with dashed lines (the thinner dashed lines further assume cross-correlated measurements). It is clear that, even without any modifications, existing detectors, especially GEO600, can probe a sizeable portion of the parameter space that is currently inaccessible to other experiments (the shaded grey region denotes existing constraints from different types of experiments, principally searches for equivalence-principle-violating fifth forces) and is physically relevant (the pale green region represents the parameter space that is technically natural for a new-physics cutoff scale of $\Lambda \sim 10$ TeV).

Conclusions GW detectors can be powerful probes of particle physics, without any kind of hardware modifications. Methods already developed for GW searches can be readily adapted to dark matter searches, at low or extremely low computational cost. What changes is the interpretation of results, and how we verify or falsify possible dark matter candidates. Though only one search has been performed for dark matter using LIGO data so far, the synergy between particle and GW physics is growing quickly, and in the future, will allow us to probe interesting portions of the parameter space that have been traditionally inaccessible to particle physics experiments, without needing complex interaction models.

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