Snowmass2021 - Letter of Interest

Search for gravitational waves from ultralight boson clouds around black holes

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 boson particles, including those conjectured to solve problems in particle physics, high-energy theory, and cosmology, could form clouds around rapidly rotating black holes. Such clouds are expected to emit continuous, quasimonochromatic gravitational waves that could be detected by gravitational-wave detectors. Existing techniques used to search for continuous gravitational waves from spinning neutron stars can be modified and applied to searches for ultralight bosons, which are largely inaccessible to other conventional experiments. Analyses have been conducted using data collected by existing Advanced LIGO and Virgo detectors, yielding interesting constraints on the properties of these yet-undiscovered particles. The future ground-based detector network with improved sensitivity as well as space-based gravitational-wave detectors will promise the capability of probing a large parameter space of the ultralight bosons, or even a direct detection. The constraints obtained are of great interest and complementary to related research in particle physics, high-energy theory, and cosmology. If there is a detection, detailed measurements of the gravitational-wave signal morphology would provide invaluable information about the properties of the new particle, and would shed light on the fascinating connection between black holes and particle physics.

Motivation. Ultralight boson particles, including scalar (spin 0), vector (spin 1), and tensor (spin 2) fields, have been predicted under several theoretical frameworks to solve problems in particle physics, high-energy theory and cosmology [1–8]. One well-motivated example is the quantum-chromodynamics (QCD) axion, a pseudo-Goldstone scalar boson proposed to explain the strong charge-parity (CP) problem [1–3]. Other examples include a variety of axion-like particles with masses in a range spanning between 10^{-33} eV and 10^{-10} eV (e.g., string axiverse [4]) and ultralight vector particles (e.g., hidden photons arising from string theory [5]). These bosons could also be a significant component of dark matter [6–8].

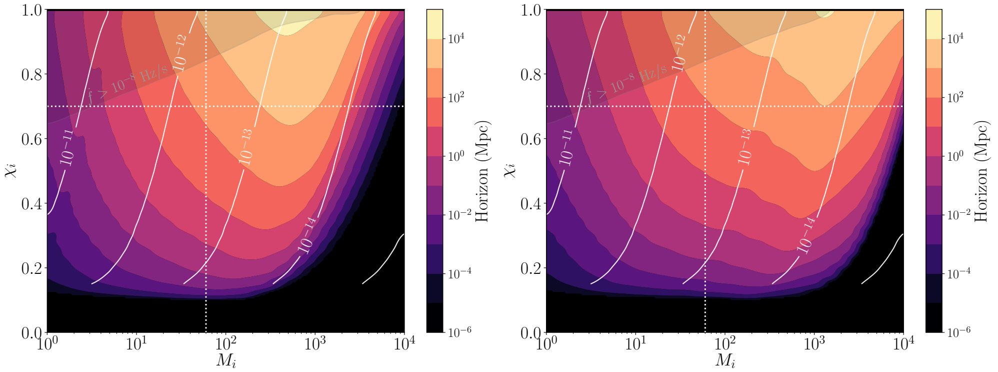
These proposed new particles are difficult to detect by conventional experiments, due to their extremely small mass and weak interaction (if any) with Standard Model particles. For example, existing constraints on the existence of the QCD axion and its mass ($\lesssim 10^{-3}$ eV) obtained from conventional experiments are based on particular assumptions of its expected coupling to the Standard Model [9, 10]. However, as predicted by theory, a mass range of $\lesssim 10^{-10}$ eV is favored for the QCD axion [11]. For such conjectured bosons with ultralight mass and vanishing interaction with the Standard Model, gravitational coupling would be the only possible way to study them.

Around a rapidly spinning black hole (BH), if there exists a fundamental ultralight boson field, it is expected to grow when the superradiance condition is satisfied [12–16]: $\omega_\mu/m < \Omega_{\rm BH}$, where $\omega_\mu = \mu/\hbar$ is the characteristic angular frequency of a boson with rest energy μ, m is the boson azimuthal quantum number with respect to the rotation axis of the BH, and $\Omega_{\rm BH}$ is the angular speed of the BH's outer horizon. For a BH with mass M, when the Compton wavelength of the particle is comparable to the characteristic length of the BH, i.e., $\hbar c/\mu \sim GM/c^2$, the superradiant instability is maximized, and thus the occupation number of ultralight bosons grows exponentially, forming a macroscopic cloud comprising $\sim$10% of the BH mass. After forming, the bosons in the cloud can annihilate, which would generate continuous, quasi-monochromatic gravitational waves (GWs) over a long lifetime [11, 17–24]. By searching for such GW signals, ground-based detectors (e.g., [25–29]), and space-based detectors (e.g., [30]) could probe bosons with masses in the ranges of $10^{-14} \lesssim \mu/\text{eV} \lesssim 10^{-11}$ and $10^{-19} \lesssim \mu/\text{eV} \lesssim 10^{-15}$, respectively, which are largely inaccessible to conventional experiments [19, 21, 22, 31] (but also see methods like [32]).

Sources and searches. Searches have already been carried out with existing ground-based GW detectors. An analysis was conducted on data from the first Advanced LIGO observing run (O1), searching for a stochastic GW background from boson clouds, which excluded a mass range of $2.0 \leq \mu/(10^{-13}\,\text{eV}) \leq 3.8$ at 95% credibility, under optimistic assumptions about BH populations [33]. It is of particular interest, however, to search for signals from individual clouds. Primary types of sources include: (1) remnant BHs from compact binary coalescences (CBCs) [34], (2) known BHs in X-ray binaries [18, 35, 36], and (3) isolated BHs in the Milky Way.

Nearby remnant BHs from detected CBC events are ideal targets [20, 23, 34]. The age of the newly born remnant BH is perfectly known, and the BH's intrinsic parameters (mass and spin) can be inferred through the CBC parameter estimation. This enables accurate theoretical predictions of the GW signal waveform from the boson cloud around the remnant BH. Moreover, the extrinsic parameters, e.g., the sky position and orientation of the source, can also be well measured for a sufficiently loud CBC event, allowing us to conduct a dedicated, efficient follow-up search for the conjectured cloud in the detector data. However, detection prospects for CBC remnants using existing detectors are penalized by the typically large luminosity distances. Future third-generation detectors, in contrast, promise a detectable luminosity distance up to $\sim 10^4$ Mpc for scalars with mass $10^{-14} \lesssim \mu/\text{eV} \lesssim 10^{-13}$ (e.g., see Fig. 1) [31, 37–41].

Known BHs in X-ray binaries [35, 36] are much closer and hence potentially within the detectable range of existing detectors. Constraints on the boson mass have already been suggested from spin measurements of BHs in X-ray binaries, roughly disfavoring the mass range of $10^{-12} \lesssim \mu/\text{eV} \lesssim 10^{-11}$ for axion-like



(a) Cosmic Explorer

(b) Einstein Telescope

Figure 1: (Fig. 12 in Ref. [31]) Maximum detectable luminosity distances (color) for optimal scalar clouds around BHs with initial mass M_i and spin χ_i for (a) Cosmic Explorer and (b) Einstein Telescope (one year of observation by a single detector). White contour lines indicate the values of the corresponding boson rest-energy μ/eV.

scalars [19, 42, 43] and $10^{-13} \lesssim \mu/\mathrm{eV} \lesssim 10^{-11}$ for vectors [23, 42]. There are, however, some challenges associated with these sources: The age and history of these systems are largely uncertain; there might be impact from the systematics in the BH spin measurements [44, 45]; the active astrophysical environments surrounding these BHs needs to be better understood [19, 23, 46]. In addition, the Doppler modulation due to the BH motion within the binary needs to be accounted for, increasing the complexity of these searches.

Isolated BHs in the Milky Way are also extremely interesting [19–22], due to their expected abundance and proximity to Earth, and as they could provide a cleaner signal compared to the X-ray BHs. The lack of electromagnetic counterparts, however, requires searching over a larger parameter space (with reduced sensitivity) since in general no prior information of the BH position and parameters is available.

The search for GW signals from boson clouds around spinning BHs is conceptually similar to the "standard" searches for continuous waves (CWs) from individual, asymmetric spinning neutron stars [47–49]. We can take advantage of the existing methods and framework developed for standard CW searches, and apply them to searching for signals from individual boson clouds. A semi-coherent, computationally efficient method using a collection of fast Fourier transforms (FFTs) computed over various durations (from hundreds to thousands of seconds), has been designed and implemented for all-sky CW searches [50]. An estimate of the detection reach for vector boson condensates, derived from all-sky CW searches in Advanced LIGO O1 has been presented in [51]. The first constraints on the scalar boson mass (in a range $\sim 10^{-13}$ eV) have been derived in [52], using strain upper limits obtained from all-sky CW searches in the second observing run of Advanced LIGO (O2). The BH population is considered for characterizing ensemble signals from galactic isolated BHs [53]. Ref. [31] modeled the signal waveforms for individual sources, and demonstrated the suitability of a specific search algorithm based on a hidden Markov model to efficiently search for signals from a known sky position [54–56]. A dedicated search for GWs from ultralight scalars in Cygnus X-1 was conducted using Advanced LIGO O2 data [57], with and without considering the nonlinear self-interaction of the bosons [4, 18, 19, 58, 59]. Direct constraints on the boson mass and decay constant have been obtained [57]. An all-sky search for scalars [50], a directed search for vectors in galactic X-ray binaries [50], as well as follow-up searches for CBC remnant BHs [31] in the latest and upcoming observing runs are being planned [60]. In addition to remnant BHs from CBC events, individual pre-merger BHs in compact binary systems are also proposed to be interesting CW sources for ground-based detectors, when those inspirals become accessible to the LISA detector, allowing for the measurement of the source properties [61].

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