Ultrastable Optical Cavity as a Gravitational Waves Bar Detector

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***Summary*— We propose application of a table-top ultra-stable cavity as a resonant-mass gravitational wave detector in a kHz regime. We show that future generations made from already known materials can be sensitive enough to observe signals from the neutron stars and subsolar-mass binary black holes mergers, and from the ultralight bosons formed through black hole superradiance.**

Keywords—optical cavity; resonant-mass detector; Weber bar; gravitational waves ; thermal limit; superriadiance; axion; dark matter

I. INTRODUCTION

Existence of the gravitational waves (GWs) was theoretically predicted by Einstein in 1916 [1] and experimentally confirmed a century later by LIGO&Virgo Scientific Collaboration using two Michelson interferometers [2]. Range of the maximum sensitivity for existing interferometer observatories spans between ~10 Hz and several kHz. Since gravitational radiation has a continuous spectrum limited around 10^{-19} Hz by the age of the Universe, many detectors and detecting methods has been proposed [3]. The first generation of detectors was based on mechanical resonance in a large (over 1-ton) high Q aluminum cylinders that is triggered by gravitational wave flying through the detector [4]. Many detectors of this type was build and improved through the years and none of them registered any confirmed gravitational signal.

The ultimate limit of the GWs detection is set by thermal processes [5]. We can mitigate them by lowering the temperature or using new component's material with better inner properties, such as quality factor or Young modulus [6, 7].

We propose to use a cryogenic ultra-stable cavity made from present-day components as a resonant-bar detector with sensitivity superior to other resonant-mass detectors in the kHz frequency regime for the observations of neutron stars and subsolar-mass black holes (BHs) mergers [8, 3], and ultralight bosons (such as axions and axion-like particles) formed through a black hole superradiance. The latter is one of the possible solution for the strong CP problem [9] and dark matter puzzle [10].

II. METHODS/RESULTS

Proposed bar-like resonant detector can be treated as a damped harmonic oscillator driven by a gravitational radiation force [3, 4]. An amplitude of the passing GW is translated into cavity length variation with the known transfer function. With two perpendicularly aligned cavities we can measure the change in length of one of them by reading out the beat note between the lasers locked to the cavities modes. This detection is limited by thermodynamical fluctuations of the cavity elements (i.e. spacer, substrates and coatings) which can be expressed quantitatively by the fractional amplitude spectral density (ASD), using fluctuation-dissipation theorem [5, 11]. Applying analytical formulas we calculated sensitivities to GW for three exemplary cavity detectors (Fig. 1.). Despite the fact that thermal processes in the cavity spacer also induces mechanical resonance, noise of the other sources and cavity's components yields resonance shape of the sensitivity to GWs.

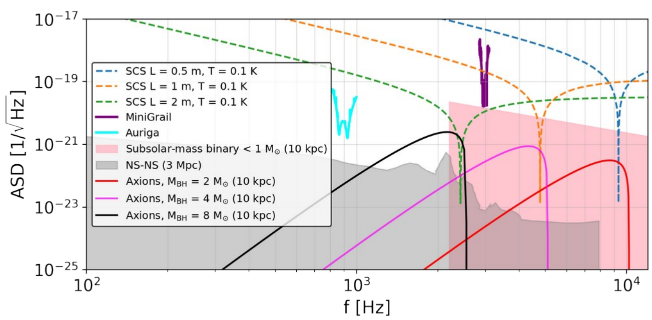

Fig. 1. Estimated sensitivities in the fractional amplitude spectral density (ASD) of two exemplary existing resonant-mass detectors [12] and three proposed cryogenic single-crystal silicon cavity (SCS) with crystalline coatings. Shaded areas depict predicted GWs signal from neutron stars merger (NS-NS) in the Local Group vicinity [8] and subsolar-mass (<1$M_\odot$) binary black holes merger in the 10 kpc distance [3]. Solid lines represent gravitational signal emitted by axions created due to superradiance phenomenon around BHs with 2, 4 and 8 solar masses ($M_\odot$) and 0.9 initial spin for 10^6 s coherent integration time [14].

To reach calculated thermal noise limit in the wide range of frequencies cavity must be effectively isolated and susceptible to any ambient perturbations, such as vibrations, vacuum and temperature fluctuation [13]. Therefore cavity must resides in the ultra-high vacuum housing and several layers of passive shields lying on active anti-vibrational platform. Today's best cavities are composed of a single-crystal silicon spacer and dielectric or crystalline-coated mirrors at cryogenic temperatures at 4K. They obtain relative length instability at the level of low 10^{-17} at 1 Hz [7].

Position of the mechanical resonance depends on the internal material properties (i.e. Young modulus and density) and length of the spacer. Even though cavity detector is sensitive to signal in a wide spectra, resonance gives at least order of magnitude better sensitivity. By adjusting mentioned parameters we can set up and maneuver resonance position to detect GWs events, such as binary neutron stars merger [8], subsolar-mass BHs mergers [3], and light bosonic fields such as axion-like particles [13].

III. CONCLUSIONS

We presented a proposal to use an ultra-stable optical cavity as a resonant-mass GWs detector in the kHz regime, which allows receiving signals from sources like binary neutron star and BH mergers and possible beyond the standard model ultralight bosons such as axion-like particles created by superradiance around BHs.

ACKNOWLEDGMENT

The "A next-generation worldwide quantum sensor network with optical atomic clocks" project (TEAM/2017-4/42) is carried out within the TEAM IV Programme of the Foundation for Polish Science co-financed by the European Union under the European Regional Development Fund. This project has received funding from the EMPIR Programme co-financed by the Participating States and from the European Union's Horizon 2020 Research and Innovation Programme (EMPIR 20FUN08 NEXTLASERS), The project is performed at the National Laboratory FAMO (KL FAMO) in Toruń, Poland and were supported by a subsidy from the Polish Ministry of Science and Higher Education.

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