論文の内容の要旨

論文題目

Modeling and Searching for Stochastic Gravitational-waves Backgrounds from Ultralight Boson Particles

(極低質量ボゾン粒子からの背景重力波のモデリングおよび探査)

氏名：塚田　怜央

Since the first detection of gravitational waves (GWs) in 2015, the field of GW astronomy has been successfully flourished with many subsequent observations. One of the next targets of GW signals is a stochastic gravitational-wave background (SGWB), superposed GW signals from distant unresolvable sources in the Universe. Recently, it was proposed that a search for a SGWB using current ground-based GW detectors, e.g. advanced LIGO, can be used to probe the existence of exotic boson particles with extremely small mass $m_b \sim 10^{-13}$ eV via a phenomenon called *superradinace instability* around a rotating BH. Such particles are predicted by beyond-Standard-Model scenarios and are expected, if present, to provide a solution to the strong CP problem in the particle physics as well as serve as a dark-matter candidate in the cosmological context. The gravitational dynamics involved in the BH superradiance yields a means of probing such particles complementary to the conventional model assuming the boson-photon coupling. Therefore, whether or not one detects the signal from the bosons, the GW search would be able to provide a meaningful implication from the perspectives of the particle physics and cosmology. This thesis describes modeling of the predicted SGWB spectrum for models of the minimally-coupled massive scalar and vector bosons and the search results of such a signal using advanced LIGO.

The superrandiant instability is a unstable system caused by massive bosonic fields extracting energy and angular momentum from a rotating BH, and forming quasi-bound states with a successive energy amplification. While the bosonic field starts to grow exponentially with the

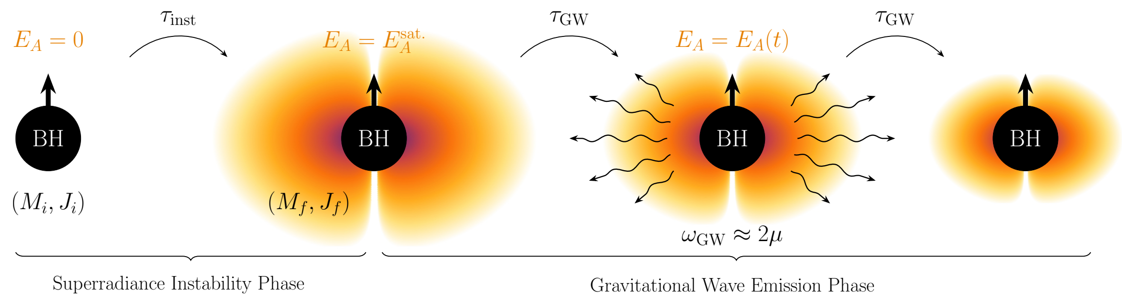

Figure 1: Cartoon picture of superradiant instability shown in Tsukada *et.al.* 2020.

timescale of $\tau_{\rm inst}$, the BH loses its mass and angular momentum accordingly. This instability continues until the BH spins down to the point where the superradiance condition starts to be saturated. By that time, the bosonic field would become boson condensate, which we call macroscopic "cloud", and its energy scale can be typically $\sim$ 10% of the BH mass. Eventually, the quadrupole moment of the cloud induces characteristic gravitational radiation. The BH perturbation theory predicts the GW emission with the nearly monochromatic frequency that depends on the boson mass over the timescale of $\tau_{\rm GW}(\gg \tau_{\rm inst})$, during which the gravitational emission dissipates the energy of the boson cloud until its energy becomes negligible. Fig. 1 shows a cartoon picture of the superradiant instability induced by massive bosonic fields.

Based on the unstable behavior of the two types of bosonic fields, which is discussed in Chapter 3, we note that whole dynamical timescale for the vector field is several order-of-magnitude shorter than that for the scalar field. In chapter 4, we calculate the SGWB spectra predicted from these boson cloud models and find that the significant difference in the GW emission timescale leads to the enhancement of the background amplitude for the vector model with the mass $\sim 10^{-13}$ eV (see Fig. 2 for comparison). Interestingly, assuming the isolated BHs and BBH merger remnant as the entire BH population, we identify a certain range of the boson masses that yields potentially detectable SGWB signal even with the current sensitivity of advanced LIGO, which implies our capability to place a meaningful constraint on the boson masses using a null result of the SGWB search.

Chapter 6 provides the results of our studies using a Bayesian-based search pipeline to look for the SGWB signal of the superradiant instability. Our injection test suggests that the search pipeline can be sensitive to scalar mass of around 1.8×10^{-13} eV to 7.5×10^{-13} eV and to vector mass of 0.4×10^{-13} eV to 9.4×10^{-13} eV, respectively. Considering a more realistic situation where SGWBs from a population of compact binary coalescences and from a boson cloud model both are present in data, we perform a model-selection test with injections of the both models and show that we can distinguish the boson cloud SGWB at around 3×10^{-13} eV(1×10^{-13} eV) for the scalar (vector) cloud model.

Lastly, we conduct a search for this kind of SGWB from each scalar and vector cloud model using the data from advanced LIGO's first and second observing runs. We do not find any strong evidence of such SGWB signal. This allows us to place the following constraints: for the pessimistic case, we exclude scalar mass of $m_b \approx 10^{-13}$ eV and similarly vector mass around $m_b \approx 10^{-13}$ eV for relatively large BH spin. On the other hand, for the optimistic case, scalar

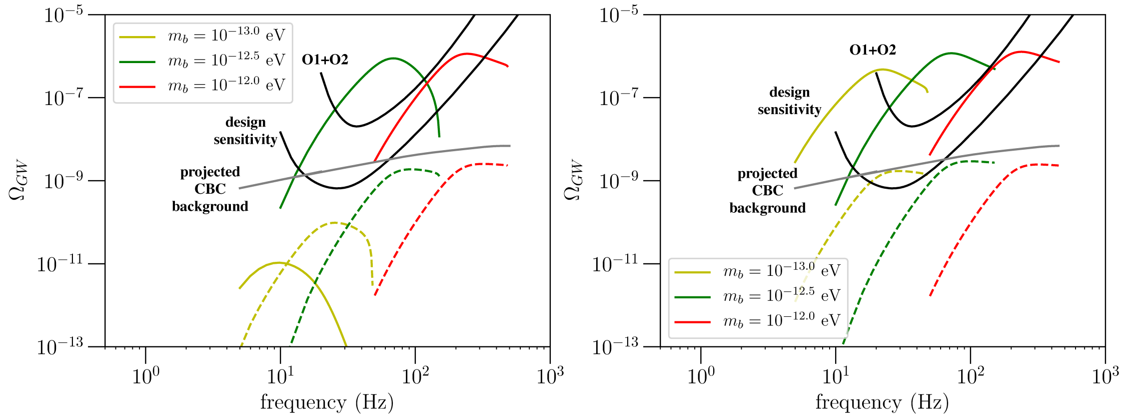

Figure 2: Energy density spectra produced from scalar (left) and vector (right) cloud systems in the LIGO band. The black solid curves represent the advanced LIGO's sensitivity for the first (O1) and second (O2) observing runs as well as the design sensitivity. Also, the solid curves in color show the contribution from the isolated BHs, whereas the dashed curves are the BBH remnants.

mass of $m_b = 2 \times 10^{-13}$ eV to 6×10^{-13} eV and vector bosons mass of $m_b = 0.8 \times 10^{-13}$ eV to 6.0×10^{-13} eV is disfavored at a 95% confidence level regardless of the BH spin. We highlight that these are the first constraints made on the boson masses based on a rigorous SGWB search.