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BOILING UNIVERSE: PHASE TRANSITIONS IN THE EARLY UNIVERSE AND THEIR GRAVITATIONAL-WAVES SIGNATURE

Description for general public

The Universe started in the hot Big Bang and later expanded and cooled down. During the early times it was filled with hot dense plasma of fundamental particles. At some point the electrons and protons combined to form hydrogen atoms. Since then, light can propagate freely since there are no free electrically charged particles that would distract it. The radiation from the moment of recombination, which was about 379 thousand years after the Big Bang, has been observed (this is the so-called cosmic microwave background radiation, CMB) and taught us a lot. However, we will never be able to see any electromagnetic radiation originating from times preceding recombination. We need an entirely new way of perceiving the Universe in order to find souvenirs from its infancy.

There is strong evidence that interesting physical phenomena happened right after the Big Bang. With the discovery of the Higgs boson, the mechanism of spontaneous symmetry breaking as a source of masses for the electroweak intermediate bosons $W^\pm$ and Z was confirmed. These masses arise from interactions with the Higgs field. It can be explained in terms of an analogy, in which the intermediate bosons propagate in a "Higgs fluid". If the fluid has zero density it is easy to propagate and particles behave as massless, if the fluid is dense it is hard to propagate and particles behave as massive. The aforementioned symmetry breaking corresponds to a change of the "density" of the Higgs field. When the fundamental fields are considered in the context of temperature evolution of the Universe, it turns out that the symmetry breaking is a physical process taking place around 10 picoseconds after the Big Bang. The nature of this process is not known yet but many theories expect that it should correspond to a first-order phase transition. A phase transition is a change of properties (phase) of a substance, e.g. when water boils it undergoes a transition from the liquid to the gaseous phase. First order transition involves release or absorption of latent heat. The symmetry-breaking phase transition proceeds similar to the process of boiling water — bubbles filled with massive phase (with nonzero "density" of the Higgs field) form within the massless phase (with zero "density") and expand until they fill the whole Universe. In this process the whole Universe is boiling and large latent heat is released. This violent event can leave an imprint in the spacetime in the form of gravitational waves.

First gravitational waves, originating from a collision of two black holes, have been observed in 2015. This unprecedented observation opened a new window through which we can "listen" to the Universe. The "listening" analogy is often used in the context of gravitational waves to emphasize that their nature is fundamentally distinct from electromagnetic waves which are the base of the traditional astronomy. In 2030' a new space based detector LISA (Laser Interferometer Space Antenna), which will be sensitive to gravitational waves resulting from phase transitions, is scheduled to be launched. This major breakthrough will allows us to hear what happened behind the CMB curtain.

In order to fully benefit from such incredibly challenging measurements we need to prepare by deepening our understanding of the processes that we aim to study and providing theoretical predictions of the signal. Contributing to this effort is the main objective of the present research project. More specifically, I aim to improve the understanding of the dynamics of the phase transition, in particular the expansion of the bubbles of the massive phase. Moreover, I will improve the theoretical tools used to describe this process. Furthermore, I will provide theoretical predictions for the gravitational-wave signal for underlying models of fundamental interactions. In addition, I will study how the properties of the phase transition can affect the observed dark matter and baryon-antibaryon asymmetry. Finally, I will strive to exploit the interplay between the particle physics and gravitational waves in order to use the LHC data in combination with the LISA data in a most insightful way.

To sum up, the forthcoming LISA detector will open a window through which we will be able to listen to the nascent Universe. To understand the message we first need to learn (and develop) the language of gravitational waves. Now it is the right time to do it.