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Phase transition in the early Universe.
From precise description to phenomenological predictions.
Outreach abstract

About 14 billion years ago the Universe started expanding and cooling down after the Big Bang. The early Universe was filled with quark-gluon plasma and other elementary particles. About a picosecond after the Big Bang the Higgs field underwent a change of its properties and elementary particles gained mass. Later, quarks and gluons formed protons and neutrons and after a few minutes, the Universe was filled with protons and electrons with a small admixture of helium and deuterium nuclei. In such an environment, rich in electrically charged particles, photons – the particles of light (excitations of the electromagnetic field) – were constantly absorbed and radiated away. Photons produced at that epoch could not propagate on large distances and, thus, transmit information about the early Universe. Conditions changed only about 380 thousand years later when electrons and protons combined to form electrically neutral hydrogen atoms. At that moment, the cosmic microwave background (CMB) radiation was released. It has been measured with increasing precision and is a source of unique information about the Universe. However, we will never observe electromagnetic radiation which would be older than CMB. This fact imposes a hard cutoff on the capabilities of traditional astronomy based on electromagnetic radiation, i.e. light of different frequencies (visible and invisible to human eyes).

Prospects for learning about the early Universe have radically changed after the first direct observation of gravitational waves in 2015. Even though the observed signal originated from the merger of two black holes, which happened only 1.3 billion light years away from the Earth, it marks the dawn of the era of gravitational-wave-based astronomy. Gravitational waves can propagate freely also in the very early Universe, therefore, gravitational-wave astronomy allows us to reach out to epochs, which cannot be accessed with the use of electromagnetic radiation. It allows us to reach where the sight does not reach – to use a twisted paraphrase of one of the most widely-known Polish poems.

The phase transition associated with the generation of elementary particles' masses, mentioned in the introduction, is one of the phenomena potentially testable with the use of gravitational waves and it is the central subject of the research project presented here.

The Higgs field interacts with other particles in a way that depends on its properties. For simplicity, the quantity determining the strength of this interaction will be referred to as "density". Particles travelling through a "thin" Higgs field do not have a mass, whereas those propagating in a "thick" Higgs soup are massive. Conversion from the former state to the latter corresponds to the aforementioned phase transition. We do not know the exact nature of this transition – it could have corresponded to smooth evolution or a rapid jump. The latter scenario is of interest to us.

It can be compared to boiling water. In a Universe filled with "thin" Higgs field and massless particles (in the proposed analogy it corresponds to liquid water), bubbles filled with "thick" Higgs and massive particles (corresponding to water-vapour bubbles) start to appear. The bubbles expand and collide until they fill the entire Universe. As opposed to the boiling of water, the phase transition associated with mass generation is accompanied by an energy release. This energy is partially converted into the energy of gravitational waves which can reach the Earth. Laser Interferometer Space Antenna (LISA), a space-based gravitational-wave detector sensitive to a signal from the phase transition, will start operating in the 2030s.

Within the project presented here, I will study various aspects of the phase transition. One of the elements, still lacking thorough understanding, is the dynamics of expanding bubbles, in particular their velocity. Improving the precision of estimates of this parameter (relevant for the experimental predictions regarding gravitational-wave signal) is one of the aims of the project. Moreover, I will work on theoretical methods, which will allow us to capture all key features of this phenomenon. Furthermore, I will explore phenomena which are associated with the phase transition, such as particle production (including dark matter), generation of the asymmetry between ordinary matter and antimatter, and production of primordial black holes.

The main objective of the project presented here is an exploration of the phase transition – a phenomenon which occurred about a picosecond after the Big Bang, nonetheless is potentially experimentally testable. Soon enough, thanks to great experimental work, will be able to appreciate "photographies" of the infant Universe. To see something in them we need to prepare well.