Equations of state for phase transitions in the early universe

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The cosmic microwave background from the era of recombination about 370 000 years after the Big Bang is the earliest time that we can directly investigate with telescopes based on electromagnetic radiation. Prior to this the universe consisted of non-transparent plasma, which makes direct measurements on the early universe difficult. However, gravitational waves interact so weakly with matter that the universe has been transparent to them from the very early moments of the Big Bang. Therefore gravitational waves are a highly useful source of information on the early evolution of the universe. [1]

In the Standard Model the electroweak phase transition, also known as the Higgs transition, is a crossover instead of a true phase transition. However, various extensions of the Standard Model predict, that there would be first-order phase transitions around the electroweak scale. [1] In this case as the temperature decreased, the early universe transitioned from the high-temperature phase to the low-temperature phase through bubble nucleation, growth and merger. The collision and movement of the bubble boundaries through the plasma would produce sound waves, as predicted by the Sound Shell Model. [2] These sound waves would be so intense that the gravitational waves they cause could still be detected with the upcoming LISA spacecraft, the Laser Interferometer Space Antenna. [3]

The power spectrum of the gravitational waves depends on five key parameters: the nucleation temperature T_n, the phase transition strength parameter α_n, the bubble wall speed v_w, the transition rate parameter β and the sound speed c_s. Deriving these values, especially the sound speed c_s, from the underlying particle physics requires modelling the plasma and its flow through the bubble walls by an equation of state. The more realistic equation of state we can use in the simulations, the more accurate correspondence we will get between the five key parameters and the gravitational wave spectrum. By measuring the gravitational wave spectrum we can determine the values for these parameters and eventually distinguish between different extensions of the Standard Model. [3]

References

[1] Chiara Caprini et al. "Detecting gravitational waves from cosmological phase transitions with LISA: an update". In: *Journal of Cosmology and Astroparticle Physics* 2020.3 (Mar. 10, 2020), pp. 024–024. ISSN: 1475-7516. DOI: 10.1088/1475-7516/2020/03/024. URL: https://iopscience.iop.org/article/10.1088/1475-7516/2020/03/024 (visited on 10/27/2021).

[2] Mark Hindmarsh and Mulham Hijazi. "Gravitational waves from first order cosmological phase transitions in the Sound Shell Model". In: *Journal of Cosmology and Astroparticle Physics* 2019.12 (Dec. 23, 2019), pp. 062–062. ISSN: 1475-7516. DOI: 10.1088/1475-7516/2019/12/062. URL: https://iopscience.iop.org/article/10.1088/1475-7516/2019/12/062 (visited on 04/27/2021).

[3] Mark Hindmarsh et al. "Phase transitions in the early universe". In: *SciPost Physics Lecture Notes* (Feb. 15, 2021), p. 24. ISSN: 2590-1990. DOI: 10.21468/SciPostPhysLectNotes.24. URL: https://scipost.org/10.21468/SciPostPhysLectNotes.24 (visited on 04/28/2021).