Primordial Gravitational waves from Cosmic Strings and Inflation

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Since they were directly detected from binary black hole mergers by the LIGO-Virgo Collaboration, gravitational waves (GW) have transformed our understanding of the universe. Beyond these astrophysical events, GWs also serve as powerful probes of early universe physics through both linear and higher-order tensor perturbations. In this work, we investigated two different sources of GWs, namely cosmic strings and scalar perturbations.

In the early universe, symmetry breaking phase transitions occurred leading to the production of cosmic string networks. Cosmic strings are infinitesimally thin and extremely dense one-dimensional objects which interact with each other and themselves to produce loops. These loops detach themselves from the network and decay via gravitational radiation. This gives rise to a characteristic stochastic gravitational wave background (SGWB) detectable across PTA, LISA and LIGO bands, that may be useful in probing the underlying particle physics. Due to the recent and anticipated advancements in GW astronomy, the opportunities to investigate the SGWB generated by cosmic string loops have increased. It is therefore of upmost importance to develop an accurate characterisation of this SGWB. In this work, we modeled the evolution of cosmic string networks through the Velocity-Dependent One-Scale model. The main assumption of this model is that the dynamics of the network may be described by a single characteristic length scale and dynamical root-mean-square velocity. We started by re-deriving the analytical approximation to the SGWB as was established in [1]. In comparison with numerical results, we show that this analytical tool provides a good quantitative description of the full SGWB. However due to the complexities involved with the radiation-matter transition, during which the VOS model is not within a linear scaling regime, a full numerical approach remains the most accurate. Therefore we improved the current numerical scheme through using an advection-type equation to solve for the number density of loops. This approach allowed us to investigate different types of loop production functions, beyond the simplistic delta function approach. Our framework combines analytical and numerical approaches as well as providing a foundation for future studies on realistic loop distributions and gravitational backreaction effects on the SGWB.

Cosmological perturbations arising from quantum fluctuations of the fields present during inflation are a powerful probe of the early universe such as providing information about the underlying inflation model. These perturbations can be characterised in three different types, namely scalars, vectors or tensors, depending on their behaviour under spatial coordinate transformations. Tensor perturbations are of particular importance since they manifest as GWs. At second order in perturbation theory, scalar modes couple nonlinearly to tensor modes, acting as a source of gravitational radiation. The transverse-traceless tensor perturbations are inherently gauge-invariant at first order in a cosmological background. However, the general covariance of Einstein's equations implies that perturbations beyond first order are gauge dependent. We investigated certain solutions to this issue such as making use of second order gauge-invariant tensors such as the magnetic part of the Weyl tensor. On the other hand, scalar perturbations can induce gravitational waves during and after inflation. We concentrated on those induced during inflation and computed estimates for the corresponding power spectrum which may be tested using the numerical relativity code GRChombo.

References

[1] L. Sousa, P.P. Avelino, and G.S.F. Guedes. Full analytical approximation to the stochastic gravitational wave background generated by cosmic string networks. *Physical Review D*, 101(10), May 2020.