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The quark gluon plasma equation of state and the expansion of the early Universe

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Abstract

Our knowledge of the equation of state of the quark gluon plasma has been continuously growing due to the experimental results from heavy ion collisions, due to recent astrophysical measurements and also due to the advances in lattice QCD calculations. The new findings about this state may have consequences on the time evolution of the early Universe, which can be estimated by solving the Friedmann equations. The solutions of these equations give the time evolution of the energy density and also of the temperature in the beginning of the Universe. In this work we compute the time evolution of the QGP in the early Universe, comparing several equations of state, some of them based on the MIT bag model (and on its variants) and some of them based on lattice QCD calculations. Among other things, we investigate the effects of a finite baryon chemical potential in the evolution of the early Universe.

Keywords: Quark–gluon plasma; MIT bag model; QCD; Friedmann equations; Lattice QCD

1. Introduction

In the last ten years relativistic heavy-ion collision experiments have provided us with information about the properties of matter in the early Universe (at the time when its age was less than 10 microseconds and its temperature was higher than 150 MeV). It is believed that, during this period, the Universe was formed by a hot phase of deconfined quarks and gluons, i.e., a quark

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gluon plasma (QGP). In parallel with these experimental developments there has been a significant progress on the theoretical side, coming from the numerical simulation of finite temperature QCD on a lattice. The new findings about the nature of the QGP motivate us to investigate their consequences in the primordial Universe. This can be done by solving the Friedmann equations, which allow us to determine the precise time evolution of the thermodynamic quantities in the early Universe.

Previous works along this line and with the same motivation already exist in the literature. For a review see, e.g., [1] and for recent papers on the subject see [2,3] and references therein. Most of these works focused on the nature of the phase transition from the QGP to the hadron gas. There are exotic phenomena associated with the order of the phase transition. In [3] a realistic EOS was used in cosmological calculations. In this EOS the transition was actually a crossover and not a first order transition as commonly believed until recent years. The results showed a very smooth time dependence of various thermodynamic quantities and suggested indirectly that there are small chances for the observation of various exotic phenomena such as quark nuggets, strangelets, cold dark matter clumps, etc. Such phenomena are associated typically with first order phase transitions. Apart from these exotic phenomena, changing the equation of state we change the space–time evolution of the early Universe and this (specially when there is a phase transition) will change the emission of gravitational waves, as pointed out in [4–6] and very recently in [7]. In [8] the authors have considered different EOS for the QGP. They computed the energy–momentum tensor, performed a Fourier transform from the configuration to the momentum space and then, using a textbook formula from [9], computed the wave spectrum, i.e., the energy density radiated in gravitational waves as a function of the wave frequency. Different EOS yield different spectra and the difference is larger for higher frequencies ($\nu > 10^{-9}$ Hz). In the region $\nu > 10^{-5}$ Hz, depending on details of the phase transition, the differences can be of orders of magnitude in the spectrum. The differences might be detectable. In [4] the authors show that the eLISA/NGO (New Gravitational wave Observatory) planned for the next years (and also the Big Bang Observatory (BBO)) will be able to measure the gravitational radiation in the frequency region relevant to the quark gluon plasma physics. They show how changes in the spectrum (due to fluctuations in temperature and fluid velocity) could be observed by eLISA/NGO in the frequency region $\nu > 10^{-5}$ Hz. The authors have considered the recently published eLISA/NGO sensitivity curve.

In the early Universe the baryon chemical potential was small (and usually neglected in cosmological calculations) but we do not know exactly how small. Moreover there may have been fluctuations in the chemical potential associated with the anisotropy of positively and negatively charged particles in the QGP phase, as pointed out in [10]. It is therefore interesting to estimate the effects of a non-vanishing chemical potential on the solution of the Friedmann equations.

We believe that the Universe is homogeneous and isotropic [9]. This statement implies that the space–time can be parametrized by the Friedmann–Lemaître–Robertson–Walker (FLRW) metric which, inserted into the Einstein equations yield the Friedmann equations [9]. From these latter we can derive the following time evolution equation [2,3,11]:

$$-\frac{d\varepsilon}{3\sqrt{\varepsilon}\,(\varepsilon+p)}=\sqrt{\frac{8\pi G}{3}}dt \tag{1}$$

which allows us to find the temporal evolution of the energy density ε once we know $p \equiv p(\varepsilon)$. In this work we solve numerically the equation above using some recently proposed equations of state and compute the time evolution of some thermodynamical quantities in the early Universe,