Diffusion of density inhomogeneities in the early universe

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Abstract

Density inhomogeneities can be generated very early in the universe. They are one of the reasons for all the large-scale structures in the early universe. Density inhomogeneities play an important role in nucleosynthesis calculations and affect the phase transition dynamics. These inhomogeneities decay by particle diffusion in the early universe. We have studied the decay starting from the electroweak phase transition up to the starting of the nucleosynthesis era. We study the decay of these inhomogeneities in the early universe with and without considering the expansion of the universe. We calculate the interaction cross-section of the quarks with the neutrinos, the electrons, and the muons and obtain the diffusion coefficients. We find that the expansion of the universe causes the inhomogeneities to decay at a faster rate. We find that the inhomogeneities generated at the electroweak epoch have very low amplitudes at the time of the quark hadron phase transition. So unless inhomogeneities are generated with a very high amplitude, they will have no effect on the quark hadron phase transition. In the hadronic phase, we have considered the interaction of neutron, proton, electron, and muon. We include the interaction of the muons with the neutrons and the protons till 100 MeV. We also find that large density inhomogeneities generated during the quark hadron transition with sizes of the order of 1 km must have amplitudes greater than 10^5 times the background density to survive up to the nucleosynthesis epoch in an expanding universe.

Introduction

- Primordial cosmological fluctuations are an important part of modern cosmology as they link the current Cosmic Microwave Background Radiation (CMBR) data to the early universe.
- Baryon inhomogeneities generated in the electroweak epoch, have less chance of surviving till the nucleosynthesis epoch, hence they are often ignored.
- Here we have used relativistic diffusion equation to study the baryon diffusion in the quark gluon plasma phase.
- Here, we only look at sub horizon fluctuations. We also assume that the size of the fluctuations are larger than the mean free path of the relevant particles.

Baryon inhomogeneities in the early universe

- There are several ways in which baryon over densities can be generated in the early universe. Topological defects, decay of $z(3)$ domain wall etc.
- Lengthscale of electroweak scale inhomogeneities were about 10^{-3} cm and QCD inhomogeneities were about 1 meter.
- We have taken the amplitude of inhomogeneities as 10^4 for electroweak scale and 10^8 for QCD scale.
- Here we will discuss decay of inhomogeneities using diffusion equation considering the expansion of the universe

The Diffusion equation in the FLRW metric

- The FLRW metric for the flat space is defined by,

$$ds^2 = c^2dt^2 - a^2(t)d\vec{r}^2 \tag{1}$$

- Relativistic diffusion equation is defined by,

$$\frac{\partial}{\partial t}n(\vec{r},t) + 3H(t)n(\vec{r},t) - \frac{D(t)}{a^2}\nabla^2 n(\vec{r},t) = 0 \tag{2}$$

- We use the time - temperature relation in the radiation dominated universe to convert our time to temperature.

$$t = \frac{(0.95 \times 10^{10})^2}{T^2} \tag{3}$$

Here t is in secs and T is in Kelvin.

- We then solve the diffusion equation in the FLRW metric numerically over the entire range of temperature from 200 GeV - 200 MeV.

Diffusion in the electroweak scale

- During this epoch the most abundant particles are the quarks, electrons, muons and the neutrinos. Out of all these, it is the quarks which carry the baryon number.
- We consider two cases for diffusion depending on the mass of the particles. The quarks are lighter than the muons but heavier than the electrons.
- For the quarks moving through the muons, the diffusion coefficient is,

$$D = \frac{1}{3N}\left\langle \frac{v}{\sigma_t} \right\rangle = \left(\frac{T}{\pi m}\right)^{1/2} \frac{2^{3/2}}{3\sigma_t} \tag{4}$$

- For quark-electron and quark-neutrino case the coefficient is given by,

$$D = bT \tag{5}$$

$$b^{-1} = \frac{16\pi}{T}\int \frac{p^2dp}{3h} vp^2\sigma_t e^{-E/T} = \frac{16\sigma_t m^2 t^2}{3\pi^2}. \tag{6}$$

Here σ_t is the scattering cross-section, m is the mass of the particle and b is the mobility.

- Quark-neutrino scattering cross-section

$$\sigma_t = \frac{G_F^2 \hat{s}}{\pi} \tag{7}$$

Here G_F is the Fermi constant given by, $G_F = 1.166 \times 10^{-5} GeV^{-2}$.

- Scattering cross-section for quark-electron and quark-muon interaction is,

$$\sigma_t = \frac{4\pi Q_f^2 \alpha^2}{3s} \tag{8}$$

Decay of inhomogeneities in the quark gluon plasma phase

- We now look at baryon inhomogeneities generated during the electroweak phase transition. The horizon at these temperatures is of the order of mm scale.
- From 200 GeV where the horizon is of the order of 1 cm to 200 MeV where the horizon is of the order of 10 kms. We divide it into two parts.
- Here we have shown the decay of the inhomogeneity for electron -quark interaction

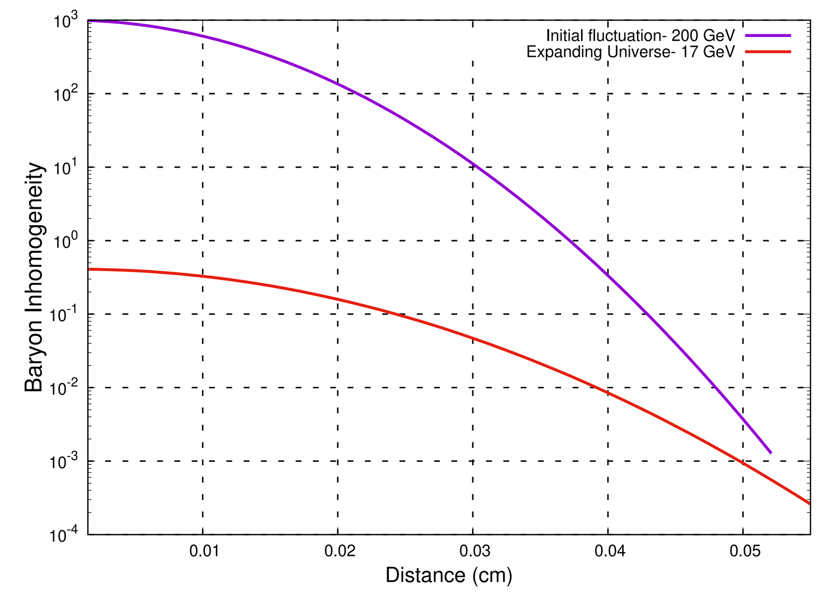

Figure 1: Decay of the fluctuation is shown in log-scale between 200 GeV - 1 GeV.

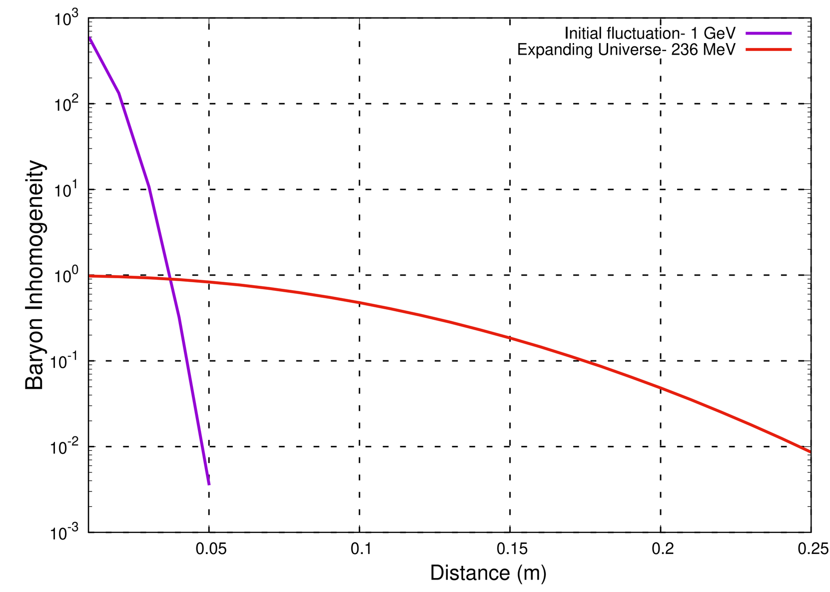

Figure 2: Decay of the fluctuation is shown in log-scale between 1 GeV - 200 MeV.

Decay of inhomogeneities in the hadronic phase

- During hadronic phase most abundant particles are the neutrons, protons, electrons and muons.
- Neutron-electron scattering diffusion coefficient is given by,

$$D_{ne} = \frac{M^2}{32m^3}\frac{1}{\alpha\kappa^2}\frac{e^{1/T}}{Tf(T)}. \tag{9}$$

$\kappa = -1.91$ is the anomalous magnetic moment, $f(T) = 1 + 3T + 3T^2$.

- As muon play a role till 100 MeV, we divide the 200 MeV-1 MeV scale into two part. We will not consider muon interaction below 100 MeV.
- Here we have shown the decay of the inhomogeneity for Neutrons.

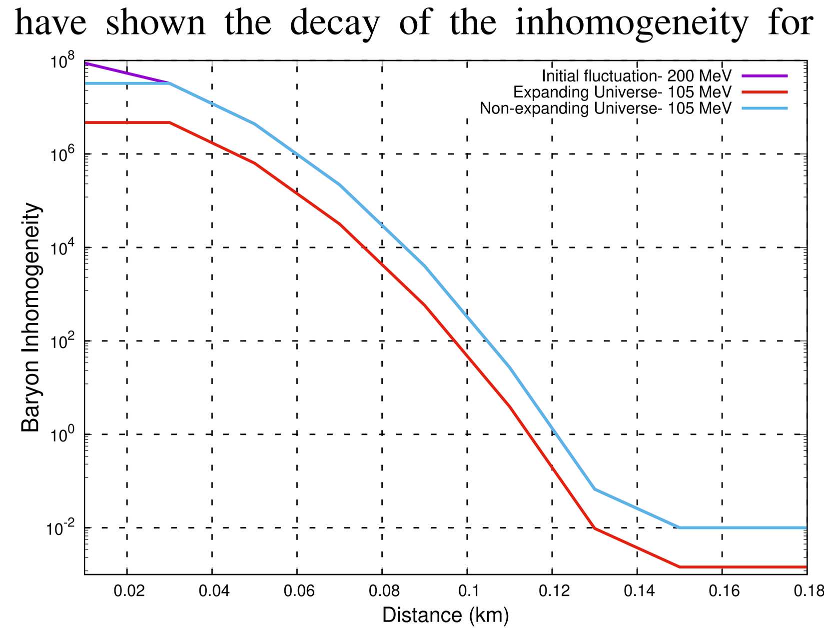

Figure 3: Decay of the fluctuation is shown in log-scale between 200 MeV - 100 MeV.

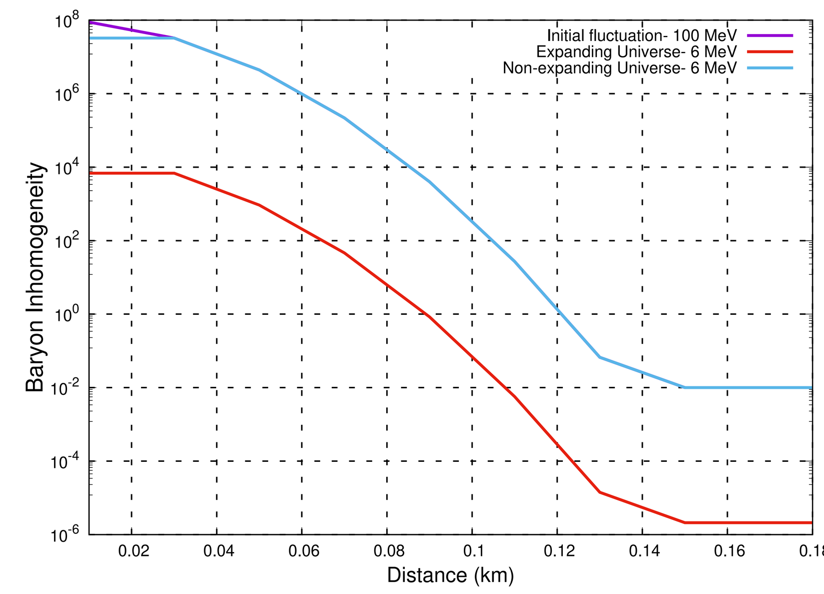

Figure 4: Decay of the fluctuation is shown in log-scale between 100 MeV - 1 MeV

Summary

- Baryon inhomogeneities generated at the electroweak scale have important consequences in the early universe. If they survive till the quark hadron phase transition they will affect the phase transition dynamics.
- We have found that baryon inhomogeneities generated in the electroweak epoch should have an amplitude greater than 10^3 for them to survive till the quark hadron phase transition.
- We have looked at the decay of baryon inhomogeneities for an expanding universe in QCD epoch where we can work with large baryon inhomogeneities.
- We find that the baryon inhomogeneities decrease by 5-6 orders of magnitude. This means that if large baryon inhomogeneities are generated by collapsing domain walls and other topological defects during the quark hadron transition they will survive till the nucleosynthesis epoch.

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