Neutrino inflation of baryon inhomogeneities in strong magnetic fields.

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Abstract

Baryon inhomogeneities formed in the early universe are important as they affect the nucleosynthesis calculations. Since they are formed much before the nucleosynthesis epoch, neutrino inflation plays a crucial role in damping out these fluctuations. Now neutrinos, in turn, are affected by magnetic fields which may be present in the early universe. In this work we study the evolution of baryonic inhomogeneities due to neutrino induced dissipative processes in the presence of a background magnetic field. We find that at higher temperatures the dissipation of the inhomogeneities are enhanced as the magnetic field increases. Our study also shows that at lower temperatures the same magnetic field may produce less dissipation. Though we limit our study to temperatures below the quark-hadron transition we do establish that magnetic fields present in the early universe affect the dissipation of baryonic inhomogeneities.

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I. INTRODUCTION

Baryon inhomogeneities are formed during various epochs in the early universe \[1\]. These inhomogeneities are important as their presence during the nucleosynthesis epoch affects the neutron to proton ratio and thus the calculated abundances of the light elements. These baryon inhomogeneities get dissipated as the universe gets cooler by the combined effects of neutrino inflation (before 1 MeV) and baryon diffusion (after neutrino decoupling). The baryon inhomogeneities have a higher baryon number density than the surrounding plasma, so to maintain pressure equilibrium with the plasma they have to have a lower temperature than the surrounding plasma. As long as neutrinos are free streaming (over the lengthscale of the inhomogeneities) they pass from the high temperature plasma to the low temperature inhomogeneities and deposit heat in them. The deposition of heat disturbs the pressure balance and the inhomogeneity increases in volume to achieve pressure equilibrium again. Thus the volume of the inhomogeneity increases while its amplitude goes down due to transfer of heat by the neutrinos. Detailed study of the dissipation of these baryon fluctuations have been carried out \[2, 3\] previously. As seen in these studies neutrino inflation reduces the inhomogeneities but in most cases is unable to wipe them out completely. This is especially true if the inhomogeneity is large. Smaller inhomogeneities are however wiped out by neutrino inflation.

The studies done previously have been done without the presence of a background magnetic fields. There are ample evidences to show that the early universe had large magnetic fields \[4\]. Recent studies have also shown that neutrinos though uncharged are affected by magnetic fields especially in the early universe plasma \[5\]. Magnetic fields increase heat loss from the background plasma by the enhanced creation of neutrino pairs by e+e- annihilation, neutrino synchrotron radiation and other processes. These neutrinos pass through the baryon inhomogeneities and increase the total heat deposited in them. In this work, we study the effect of this on the baryon inhomogeneities.

Heat loss from the background plasma by neutrinos in presence of magnetic field has been studied with respect to neutron stars and supernovae explosions. These studies are thus for much lower temperatures. \((T = 10^9K)\). Since neutrino inflation of baryon inhomogeneities occur at much higher temperatures \((T >> 10^9K)\), and very few studies have been done for such temperatures; we believe that our work will also provide a motivation to carry out
further studies of neutrino effects in higher temperature plasmas in the presence of magnetic fields.

In section II we first review heat deposition in baryon inhomogeneities, then in section III, we review neutrinos in high temperature magnetic plasmas. In section IV, we present our calculations for the dissipation of baryonic inhomogeneities, due to neutrinos in the presence of a magnetic field and give our results. In section V, we briefly discuss how we can get such strong magnetic fields before the nucleosynthesis epoch. Section VI presents our conclusions and some discussions regarding the approximations considered in this work.

II. HEAT DEPOSITION IN BARYON INHOMOGENEITIES.

Baryon inhomogeneities have a lower temperature than the surrounding plasma. Free streaming particles moving from the plasma into these inhomogeneities tend to deposit heat in them. The plasma loses heat to these inhomogeneities continuously until they are completely wiped out. Since plasma heat loss mechanism is enhanced by magnetic field, the heat deposition in baryon inhomogeneities may get enhanced. This will cause the inhomogeneity to dissipate faster. We now review heat deposition by neutrinos in baryon inhomogeneities after the quark hadron transition. If the total energy deposited by the neutrinos is $\Delta E$ and the volume increase due to the energy deposition is $\Delta V$ then,

$$\Delta V = \frac{\Delta E}{\rho_{\text{rad}}}$$  \hspace{1cm} (1)

where $\rho_{\text{rad}}$ is the energy density of the plasma in the radiation epoch. If $n_b$ be the baryon number density in the inhomogeneity and $n_{b0}$ be the baryon number density of the background plasma then the overdensity can be defined as $\delta_n = \frac{n_b}{n_{b0}}$. As baryon number is conserved, one can then obtain [3],

$$\frac{d\delta_n}{dt} = -\frac{\delta_n}{\rho_{\text{rad}} V(t)} \frac{dE}{dt}$$  \hspace{1cm} (2)

or,

$$\frac{d\delta_n}{dt} = -\frac{\delta_n}{\rho_{\text{rad}}} \frac{d\epsilon}{dt}$$  \hspace{1cm} (3)

where $\frac{d\epsilon}{dt}$ is the rate of energy density deposited in the inhomogeneity. Eq. 3 gives the evolution of the inhomogeneity with time. In the absence of a magnetic field this has been calculated both in ref. 2 and 3. It depends on the neutrino flux ($\frac{\nu_{\mu}}{\nu_{\tau}} T^3$), the weak
cross-section \((G_F^2 T^2)\), the total number of targets in the fluctuation and the average energy transfer during the collisions. Combining all these we get,

\[
\frac{d\epsilon}{dt} = 0.2G_F^2 \left(\frac{\delta T}{T}\right) T^9
\]  

(4)

The factor of 0.2 changes to 1.8 when electron-positron annihilations are taken into account \[^2\]. Hence we will take the factor to be 1.8. \(G_F\) is the Fermi constant and \(\frac{\delta T}{T}\) is the fractional temperature difference between the inhomogeneity and the background plasma. For inhomogeneities present after the quark hadron phase transition, it can be obtained by using the pressure equilibrium condition between the inhomogeneity and the plasma as, \[^3\]

\[
\frac{\delta T}{T} = \frac{\delta n_0 \eta_0}{g_{\text{eff}}}
\]  

(5)

where \(\delta n_0\) is the initial overdensity, \(\eta_0\) is the baryon to photon ratio of the plasma at that temperature and \(g_{\text{eff}}\) is the effective degrees of freedom taken to be 10.75 here. The energy density deposited in the baryon inhomogeneities due to the neutrinos depends on \(\chi \frac{\delta T}{\delta r}\) where \(\chi\) is the heat conductivity in an imperfect fluid. \(\chi\) depends upon the energy density carried by the neutrinos, the neutrino mean free path and the temperature of the plasma. \(\chi = \frac{4}{3} \frac{\rho_\nu}{T} \lambda_\nu\). \(\delta r\) is the size of the inhomogeneity. In our calculations we consider it to be the same as the neutrino mean free path. Therefore,

\[
\epsilon = \frac{4}{3} \frac{\rho_\nu}{T} \chi \frac{\delta T}{\delta r}
\]  

(6)

If \(Q\) (the emissivity) gives the rate of energy density carried by the neutrinos \((\frac{d\rho_\nu}{dt})\) from the plasma, we can obtain the rate of heat deposition in the inhomogeneity as,

\[
\frac{d\epsilon}{dt} = \frac{4}{3} Q \frac{\delta T}{T}
\]  

(7)

One thing to keep in mind over here is that the above expression is only for \(\delta r \sim \lambda_\nu\); for \(\delta r \neq \lambda_\nu\) there will be a factor multiplying it which depends on the ratio of the neutrino mean free path to the size of the baryon inhomogeneity. Once the value of \(Q\) is obtained, we can obtain the energy deposited.

III. NEUTRINOS IN MAGNETIC FIELDS.

Magnetic fields of different magnitudes have been predicted in the early universe \[^4\]. Though neutrinos are uncharged, a magnetized plasma nevertheless affects their interactions.
Since we are interested in the heat lost by the background plasma we concentrate on the $\nu - \bar{\nu}$ production from $e^+e^-$ annihilation and the neutrino synchrotron radiation in the presence of a magnetic field. Though there are many calculations of these interactions [6], we follow the analysis done by Kaminker et al. [7, 8]. This is because they have done the analysis for the largest range of temperatures. Since the temperatures we are dealing with are higher than the temperatures commonly encountered in the neutron stars we find that only the analysis of ref. [7, 8] are applicable in our case. For $T > 10^{11} K$ and for high magnetic fields the rate of neutrino energy density carried by the $\nu - \bar{\nu}$ pairs per unit volume, has been obtained in ref. [7] and the energy density carried by the neutrinos in synchrotron radiation has been obtained in ref. [8]. The plasma in our case is non-degenerate and relativistic. We see that for such a plasma, the analysis of Kaminker et al show that the dominant heat loss mechanism from the plasma depends upon whether the magnetic field chosen is quantizing or not. The neutrino emmissivity calculation depends on the number density of plasma ions occupying the Landau levels at a particular temperature. For a non-quantizing magnetic field many Landau levels are occupied, while for a quantizing magnetic field the particles mostly occupy the ground level. Thus the majority of plasma particles are incapable of emitting synchrotron $\nu - \bar{\nu}$ pairs for quantizing magnetic fields. This is reflected in the presence of an exponentially small factor in the final expression of the synchrotron loss rate which reduces the emmissivity considerably. Hence for a quantizing magnetic field, neutrino emmissivity from $e^+e^-$ annihilations dominates over the emmissivity from synchrotron radiation. The value of $Q$ for different temperatures and magnetic field have been calculated by Kaminker et al. for both $\nu - \bar{\nu}$ pair production and neutrino synchrotron radiation. We substitute these values in the equation for energy deposition obtained in the previous section and study the evolution of baryon inhomogeneities due to neutrino inflation in the presence of magnetic fields.

IV. EVOLUTION OF BARYON INHOMOGENEITIES IN THE PRESENCE OF A MAGNETIC FIELD

The inhomogeneities are mostly formed just after the quark-hadron transition which takes place around 170 MeV. Hence we will consider the evolution of the inhomogeneities around this time. Depending on the magnitude of the temperature the magnetic field is
either non-quantizing or quantizing. The two cases have to be treated in different ways. We take $T \sim 100\text{MeV}$. So, the non-quantizing magnetic field will mean $B < 4.414 \times 10^{19}\text{Gauss}$, while the quantizing fields will be, $B > 4.414 \times 10^{19}\text{Gauss}$. Since such high magnetic fields are difficult to come by in the early universe, we can safely assume that for temperatures around the quark-hadron transition, the background magnetic fields are non-quantizing. The emissivity $Q$ is then obtained for the relevant parameters from refs.\[7, 8\].

Once $Q$ is obtained we substitute it in eqn.\[7\]. Using eqn.\[8\] and the time-temperature relation,

$$t = (0.3g_{eff}^{1/2})\frac{m_{pl}}{T^2}$$

in eqn.\[8\] we get,

$$\frac{d\delta_n}{\delta_n} = K\frac{dT}{T^7}\left[\frac{d\epsilon}{dt}\right]_{\text{total}}$$

where $K = \frac{1.8m_{pl}}{(\pi^2g_{eff}^{1/2})} \sim 10^{21}\text{MeV}$ and $\frac{d\epsilon}{dt}_{\text{total}}$ is given by,

$$\left[\frac{d\epsilon}{dt}\right]_{\text{total}} = \left[\frac{d\epsilon}{dt}\right]_{\text{thermal}} + \left[\frac{d\epsilon}{dt}\right]_{e^+e^-} + \left[\frac{d\epsilon}{dt}\right]_{\text{syn}}$$

The first term on the R.H.S gives the energy deposited in the absence of a magnetic field. The second term on the R.H.S gives the energy deposited due to neutrino pair production from $e^+e^-$ annihilation and the third term on the R.H.S gives the energy deposited due to neutrino synchrotron radiation. Integrating both sides of eqn.\[8\] we find out how the inhomogeneity evolves between a certain temperature range. We consider the initial overdensity in the inhomogeneity to be $\delta_{n0} \sim 10^4$. We also make the approximation that $\frac{dT}{T}$ is constant. For a more thorough analysis one must do a proper simulation where $\frac{dT}{T}$ changes continuously.

We integrate the R.H.S. of eqn.\[8\] separately for the three different mechanisms and join them at the end to get the final expression. Let,

$$I_1 = \int \left[\frac{dT}{T^7} \times C_1T^9\right]$$

where $C_1 = 1.8G_F^2\delta_{n0}\frac{m_{pl}}{g_{eff}}$. Hence,

$$I_1 = \frac{C_1}{3}(T_2^3 - T_1^3)$$

where we have considered $T_1$ as the initial and $T_2$ as the final temperature.

For the second term, we see from ref.\[7\], for high temperatures and non-quantizing magnetic fields, the emissivity of neutrino pairs due to $e^+e^-$ annihilation is independent of the
magnitude of the magnetic field and is given by,

\[ Q = \frac{7Q_c}{12\pi} \zeta(5) \left( \frac{T}{5.93 \times 10^9 K} \right)^9 (C_v^2 + C_A^2) \quad (13) \]

where \( Q_c = 1.015 \times 10^{23} \text{erg cm}^{-3} \text{sec}^{-1} \) and \( (C_v^2 + C_A^2) = 1.675 \). Thus the second term will be similar to the first one after integration and will only have a different constant \( C_2 \). Therefore,

\[ I_2 = \frac{C_2}{3} (T_3^3 - T_1^3) \quad (14) \]

where \( C_2 = \frac{7Q_c}{12\pi} \zeta(5) (\frac{1}{5.93 \times 10^9 K})^9 (C_v^2 + C_A^2) \delta n_0 \frac{m}{g_{eff}} \). For the synchrotron radiation, the emmissivity in the high temperature, non-quantizing magnetic field is given by \[ 8 \],

\[ Q = \frac{20Q_c}{9(2\pi)^{5/2}} \zeta(5) \left( \frac{T}{5.93 \times 10^9 K} \right)^5 b^2 C_4^2 \left[ \ln \left( \frac{T}{\sqrt{b} \times 5.93 \times 10^9 K} \right) + 2.33 \right] \quad (15) \]

where \( b = \frac{B \text{ (Magnetic field in Gauss)}}{4.414 \times 10^{13} \text{Gauss}} \) and \( C_4^2 = 1.68 \). Therefore,

\[ I_3 = \int \left[ \frac{dT}{T^7} \times C_3 T^5 \left[ \ln \left( \frac{T}{C_4} \right) + 2.33 \right] \right] \quad (16) \]

where \( C_3 = \frac{20Q_c}{9(2\pi)^{5/2}} \zeta(5) (\frac{1}{5.93 \times 10^9 K})^5 b^2 C_4^2 + \delta n_0 \frac{m}{g_{eff}} \) and \( C_4 = \frac{1}{\sqrt{b} \times 5.93 \times 10^9 K} \) are constants depending on the magnetic field. Integrating, we get,

\[ I_3 = C_3 \left[ \ln \left( \frac{T_1}{C_4} \right) \frac{1}{T_1} - \ln \left( \frac{T_2}{C_4} \right) \frac{1}{T_2} + (C_4 + 2.33)(\frac{1}{T_1} - \frac{1}{T_2}) \right] \quad (17) \]

So finally we have,

\[ \delta_n = \delta n_0 \exp \left[ \frac{K}{3} (C_1 + C_2) (T_3^3 - T_1^3) + C_3 \left[ \ln \left( \frac{T_1}{C_4} \right) \frac{1}{T_1} - \ln \left( \frac{T_2}{C_4} \right) \frac{1}{T_2} + (C_4 + 2.33)(\frac{1}{T_1} - \frac{1}{T_2}) \right] \right] \quad (18) \]

We evaluate the constants and plot the change in \( \delta_n \) as a function of temperature. Constants \( C_1 \) and \( C_2 \) are independent of the magnetic field. We evaluate \( C_3 \) and \( C_4 \) for different values of magnetic fields. \( T_1 \) is taken to be 150 MeV, since we assume that the baryon inhomogeneities have been formed during the quark hadron transition which takes place around 170 MeV. The final temperature is taken to be about 100 MeV. We have taken this because below 100 MeV, our definition of quantizing and non-quantizing magnetic fields may change. This would make our analysis inconsistent.

We find that for low values of magnetic fields there is not much difference. But as we increase the value of magnetic field the difference starts increasing. For very high magnetic fields, \( B = 10^{18} G \) we see a very significant difference in the evolution of the inhomogeneity.
FIG. 1:

This figure shows the decrease in the overdensity of the inhomogeneity over the temperature range 150 MeV - 100 MeV. The solid line denotes the decrease in the overdensity in the absence of the magnetic field while the dashed line shows it for a magnetic field of magnitude $B = 10^{18} G$.

This is shown in Fig.1. The solid line denotes the evolution of the inhomogeneity in the absence of a magnetic field while the dashed line denotes the evolution in the presence of the magnetic field. Clearly the inhomogeneities get wiped out faster in the presence of a magnetic field. Of course, the magnetic field considered is very high, but we will discuss later on the possibility of such high magnetic fields being present in the early universe. Even for $B = 10^{17} G$, the evolution is not exactly the same. For lower values of the magnetic field, the difference in the evolution is still smaller, but there is always a finite difference with the field free case.

All this is when the temperature is above 100 MeV. However, neutrinos decouple only after 1 MeV. So these effects will also be there below 100 MeV. Only now the non-quantizing fields will have to be below $4.414 \times 10^{17}$ Gauss. The effect here is similar as before, as the field is increased the inhomogeneity decreases faster.

We now do a similar analysis for quantizing fields. Here the emissivity from the e+e-annihilation is given by [7],

$$Q = \frac{Q_e}{48\pi^3} b\zeta(3) \left( \frac{T}{5.93 \times 10^9 K} \right)^5 (C_v^2 + C_A^2).$$  \hspace{1cm} (19)$$

So that we get,

$$I_2 = \int [\frac{dT}{T^2} \times C_2 T^5]$$

where $C_2 = \frac{Q_e}{48\pi^3} b\zeta(3) \left( \frac{1}{5.93 \times 10^9 K} \right)^5 \delta_{\eta_0 \eta_{0 \text{eff}}} \delta_{\eta_0 \eta_{0 \text{eff}}} (C_v^2 + C_A^2)$ and is therefore dependent on the magnetic
field. Hence,

\[ I_2 = C_2 \left( \frac{1}{T_1} - \frac{1}{T_2} \right) \tag{21} \]

The emissivity from the synchrotron radiation in this case is given by,

\[ Q = \frac{16Q_e}{9(2\pi)^{5/2}} \left( \frac{T}{5.93 \times 10^9 K} \right)^{1/2} b^4 C_4^2 \left( 1 - \frac{9}{4e} \right) (2\pi \sqrt{2b})^{5/2} E_x \left[ -\sqrt{2b} \times 5.93 \times 10^9 K \frac{T}{T} \right] \tag{22} \]

As pointed out in ref. \[8\], this is very small due to the presence of the exponential term. When we carry out the integration we get,

\[ I_3 = C_3 [E_x \exp\left( -\frac{C_4}{T} \right) \left( \frac{1}{(C_4 T^{9/2})} + \frac{9}{(2C_4^2 T^{7/2})} + \frac{63}{(8C_4^3 T^{5/2})} + \frac{315}{(32C_4^4 T^{3/2})} + \frac{945}{(C_4 T^{1/2})} \right)] - C_3 [945 \sqrt{\pi} \text{Erf} \left( \frac{C_4}{T} \right) \left( \frac{1}{(32C_4^{11/2})} \right)] \tag{23} \]

where \( C_3 = \frac{16Q_e}{9(2\pi)^{5/2}} \left( \frac{1}{5.93 \times 10^9 K} \right)^{1/2} b^4 C_4^2 \left( 1 - \frac{9}{4e} \right) (2\pi \sqrt{2b})^{5/2} \delta_{n_0, \eta_{\text{eff}}} \eta_{\text{eff}} \) and \( C_4 = \sqrt{2b} \times 5.93 \times 10^9 K \).

Since as pointed out earlier, the synchrotron radiation does not contribute much to the overall emissivity in this region, hence the total decrease in the inhomogeneity is less in the case of the quantizing magnetic field compared to the decrease in the non-quantizing case. Here only \( C_1 \) is independent of the magnetic field. So we have to obtain \( C_2, C_3 \) and \( C_4 \) for different values of magnetic fields. The results are given in fig. 2. We see that (as observed in the previous case also) as the magnetic field is enhanced, the inhomogeneity decreases faster. The solid line denotes the evolution in the absence of magnetic fields. The dashed line indicates the evolution of the inhomogeneity at a magnetic field of \( B = 10^{18} G \), while the dotted line shows the evolution at \( B = 10^{19} G \). This decrease is less than in the previous case (fig 1), which seems to show that it is the synchrotron radiation which plays a greater role in the heat loss mechanism than the neutrino production from \( e^+e^- \) annihilation.

V. HIGH MAGNETIC FIELDS IN THE EARLY UNIVERSE.

A detailed review of magnetic fields in the early universe is given in ref. \[4\]. Here we mention only some special cases where very high field values have been postulated. Superconducting strings in the early universe may generate very high fields. In ref. \[9\], the authors have discussed the generation of magnetic fields with values as high as \( 10^{22} \) Gauss. Superconducting strings passing through the hadronic plasma after the quark-hadron transition, thus may generate very high magnetic fields over large lengthscales. Large magnetic fields have also been postulated to explain extragalactic gamma ray bursts.
This figure shows the decrease in the overdensity of the inhomogeneity in the temperature range 10 MeV - 1 MeV. The solid line denotes the decrease in the overdensity in the absence of the magnetic field, the dashed line shows it for a magnetic field of magnitude $B = 10^{18} \text{G}$ and the dotted line shows the evolution at $B = 10^{19} \text{G}$. The initial value of the overdensity at $T = 100 \text{ MeV}$ is taken to be $10^4$.

Apart from this, since after the quark-hadron transition the magnetic field evolves according to the frozen-in law [4], calculation shows that if the magnetic field is produced at the quark hadron transition with maximum helicity and there was equipartition of thermal and magnetic energy, then a magnetic field of magnitude $10^{17} \text{ Gauss}$ on the scale of 30 kms immediately after the phase transition is not implausible. Such large magnetic fields have been predicted in various models where the magnetic fields are generated by shock waves [10]. Hence it is possible to have large magnetic fields after the quark hadron transition which will affect the neutrino inflation of baryon inhomogeneities.

VI. CONCLUSIONS AND DISCUSSIONS

In conclusion we have established that strong magnetic fields do affect the inflation of baryon inhomogeneities by neutrino heating. We have seen that this effect is greater at higher temperatures and for non-quantizing fields. Our results seem to indicate that for the same value of the field, a non-quantizing field has more effect than a quantizing field. This is expected, since as mentioned before, for the quantizing field, most of the plasma particles are in the ground Landau level and therefore are incapable of emitting synchrotron radiation. This reduces the number of neutrinos depositing heat in the inhomogeneities. Now,
whether the field would be quantizing or not depends on the temperature. Since at higher temperatures, even strong magnetic fields are non-quantizing, hence the effect described here is greater at higher temperatures and stronger magnetic fields.

We have simplified our calculations using certain approximations. The temperature difference between the inhomogeneity is considered to be constant. However the temperature difference is actually related to the amplitude of the inhomogeneity and changes accordingly with it. But this change is very small. A proper investigation would involve a detailed simulation where the small temperature change should be taken into account. The result of keeping this constant is that we get the largest possible effect. As the amplitude of the inhomogeneity decreases, the temperature difference also decreases but as our results show the inhomogeneity does not decrease very rapidly so we feel that our results will not change very much even if we take the small temperature changes into account. We have also taken the size of the inhomogeneities equal to the mean free path of neutrinos at that temperature. If the inhomogeneities are larger then the neutrinos cannot penetrate the entire inhomogeneity and will affect only the edges of the inhomogeneities. However since neutrino mean free path increases as temperature decreases, most of the inhomogeneities within the horizon will have their sizes either equal to or smaller than the neutrino mean free path. For smaller size inhomogeneities, the heat deposited will be less by a factor given by the ratio of the size of the inhomogeneity to the mean free path of the neutrinos at that temperature.

We have considered baryon inhomogeneities present after the quark-hadron transition but there is the possibility of inhomogeneities being present much before that. Since these inhomogeneities may be created anytime after the electroweak phase transition, a much thorough investigation of their evolution should include the high temperature zone (100 GeV -200 MeV) also. For this one has to study neutrino interaction properties at much higher temperatures, in the presence of a magnetic field. To our knowledge, such a study has not been carried out. We hope that this work will provide a motivation to study neutrino emission in a magnetic field at GeV temperatures and its subsequent effect on the early universe.

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