Hypothetical hot primordial regions in the Universe with abnormally high metallicity

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Introduction

We suppose that stable hot regions can be formed in the early Universe. This hypothesis was put forward on the basis of the cosmic X-ray observations and IR background [1]. The cluster of primordial black holes (PBH) can be responsible for such regions. Formation of PBH clusters and their possible observational effects are now of special interest, but we do not constrain possibility of such regions appearance by PBH clusters only. PBH and their cluster formation can be the consequence of existence and breaking of some new symmetry in quantum field theory.

Nucleosynthesis

Neutrinos will be able to leave the region freely and therefore cool it down. The essential reactions of light elements and neutrinos produced are the following:

$$e^- + p \longrightarrow n + \nu_e, \quad (1)$$
$$e^+ + n \longrightarrow p + \bar{\nu}_e, \quad (2)$$
$$e^+ + e^- \longrightarrow \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau}, \quad (3)$$
$$n \longrightarrow p + e^- + \bar{\nu}_e, \quad (4)$$
$$p + p \longrightarrow D + e^+ + \nu_e + 1.44\ \text{MeV}, \quad (5)$$
$$D + \gamma \longrightarrow p + n - 2.22\ \text{MeV}, \quad (6)$$
$$n + p \longrightarrow D + \gamma + 2.22\ \text{MeV}, \quad (7)$$
$$D + p \longrightarrow {}^3He + \gamma + 5.493\ \text{MeV}, \quad (8)$$
$${}^3He + {}^3He \longrightarrow {}^4He + 2p + 12.861\ \text{MeV}. \quad (9)$$

Consider the reaction between two nuclei 1 and 2. The reaction rate is proportional to the mean lifetime τ of the nuclear species in the stellar plasma. The number density change rate of nucleus 1 caused by reactions with nucleus 2 can be expressed as

$$\left(\frac{dn_1}{dt}\right)_2 = -(1+\delta_{12})r_{12} = -n_1 n_2 \langle\sigma v\rangle_{12}. \quad (10)$$

Here r_{12} is the rate of interaction, δ_{12} is the Kronecker symbol equals one if $1 = 2$ and zero if $1 \neq 2$, n_1 and n_2 are the number densities of nuclei of type 1 and type 2, and $\langle\sigma v\rangle_{12}$ represents the product of the reaction cross section and the interacting nuclei's relative velocity v. The case of identical initial nuclei is taken into account by the presence of the Kronecker symbol. The rates per unit volume, $\gamma_i \equiv \Gamma_i/V$, for reactions listed above are respectively

$$\gamma_{ep} = n_{e^-} n_p \langle\sigma v\rangle_{ep}, \qquad \gamma_{en} = n_{e^+} n_n \langle\sigma v\rangle_{en}, \quad (11)$$
$$\gamma_{ee} = n_{e^-} n_{e^+} \langle\sigma v\rangle_{ee}, \qquad \gamma_n = \frac{n_n}{\tau_n}, \quad (12)$$
$$\gamma_{pp} = \frac{n_p^2}{2}\langle\sigma v\rangle_{pp}, \qquad \gamma_{\gamma d} = n_\gamma n_d \langle\sigma v\rangle_{\gamma d}, \quad (13)$$
$$\gamma_{np} = n_n n_p \langle\sigma v\rangle_{np}, \qquad \gamma_{dp} = n_d n_p \langle\sigma v\rangle_{dp}, \quad (14)$$
$$\gamma_{{}^3He{}^3He} = \frac{(n_{{}^3He})^2}{2}\langle\sigma v\rangle_{{}^3He{}^3He}. \quad (15)$$

The temperature balance is defined by the first law of thermodynamics

$$\Delta Q = \delta U, \quad (16)$$

where ΔQ and δU are the heat and inner energy gains (in fact, a decrease) of the matter inside the heated area, respectively. Expanding all the values one obtains

$$[(\gamma_{pp}\cdot Q_1 - \gamma_{\gamma d}\cdot Q_2 + \gamma_{np}\cdot Q_3 + \gamma_{dp}\cdot Q_4 + \gamma_{{}^3He{}^3He}\cdot Q_5) - (\gamma_{ep} + \gamma_{en} + 2\gamma_{ee} + \gamma_n + \gamma_{pp})E_\nu]dt = 4bT^3 dT \quad (17)$$

where Q_i is energy release of the respective reaction, $E_\nu \sim T$ is the energy of outgoing neutrino, $b = \pi^2/15$ is the radiation constant.Using Eq. (10) and (17) and reactions (3) - (9), we can compose the following system of differential equations.

$$\frac{d(n_n)}{dt} = n_{e^-} n_p \langle\sigma v\rangle_{e^-p} + n_\gamma n_d \langle\sigma v\rangle_{\gamma d} - \frac{n_n}{\tau_n} - n_n n_p \langle\sigma v\rangle_{np} - n_{e^+} n_n \langle\sigma v\rangle_{e^+n} \quad (18)$$
$$\frac{d(n_p)}{dt} = n_{e^+} n_n \langle\sigma v\rangle_{e^+n} + \frac{n_n}{\tau_n} + n_\gamma n_d \langle\sigma v\rangle_{\gamma d} + (n_{{}^3He})^2 \langle\sigma v\rangle_{{}^3He{}^3He} - n_{e^-} n_p \langle\sigma v\rangle_{e^-p} - n_p^2 \langle\sigma v\rangle_{pp} - n_d n_p \langle\sigma v\rangle_{dp} \quad (19)$$
$$\frac{d(n_d)}{dt} = \frac{n_p^2}{2}\langle\sigma v\rangle_{pp} + n_n n_p \langle\sigma v\rangle_{np} - n_d n_p \langle\sigma v\rangle_{dp} - n_\gamma n_d \langle\sigma v\rangle_{\gamma d} \quad (20)$$
$$\frac{d(n_{{}^3He})}{dt} = n_d n_p \langle\sigma v\rangle_{dp} - (n_{{}^3He})^2 \langle\sigma v\rangle_{{}^3He{}^3He} \quad (21)$$
$$\frac{d(n_{{}^4He})}{dt} = \frac{(n_{{}^3He})^2}{2}\langle\sigma v\rangle_{{}^3He{}^3He} \quad (22)$$
$$\frac{d(T)}{dt} = [(\gamma_{pp}\cdot Q_1 - \gamma_{\gamma d}\cdot Q_2 + \gamma_{np}\cdot Q_3 + \gamma_{dp}\cdot Q_4 + \gamma_{{}^3He{}^3He}\cdot Q_5) - (\gamma_{en} + \gamma_{ep} + 2\gamma_{ee} + \gamma_n + \gamma_{pp})E_\nu]/4bT^3 \quad (23)$$

The initial number densities of deuterium and helium are considered to be zero inside the region.

Result and discussions

The temperature evolution (Eq.(23)) follows from the equation system above. It is dominated by the cooling due to the reaction (3).

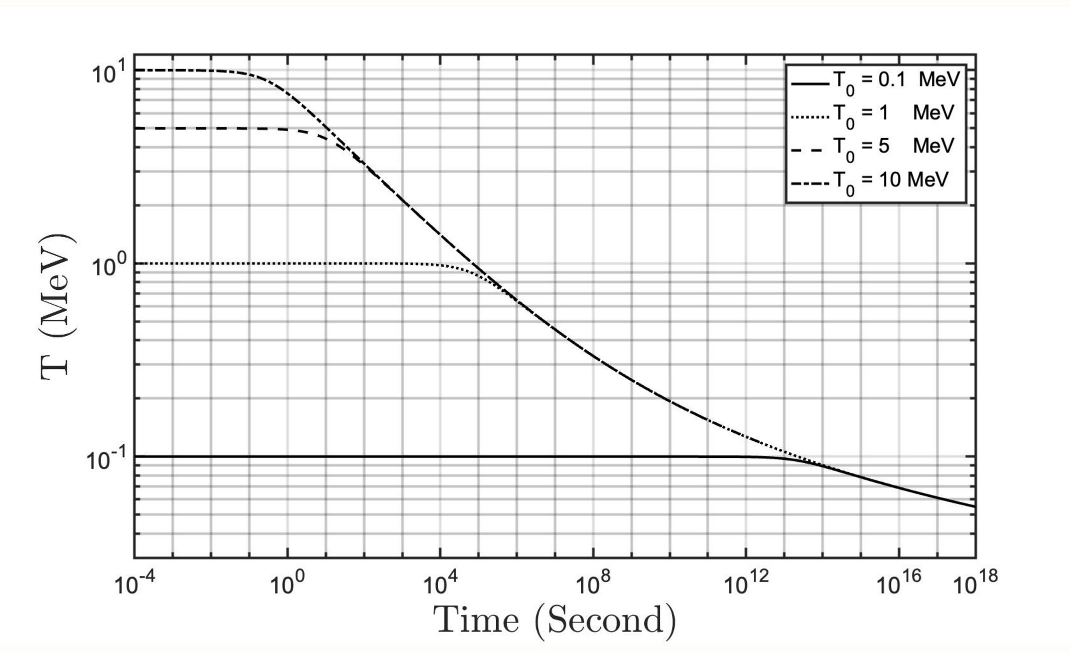

Figure 1: The time behaviour of the temperature inside the heated area.

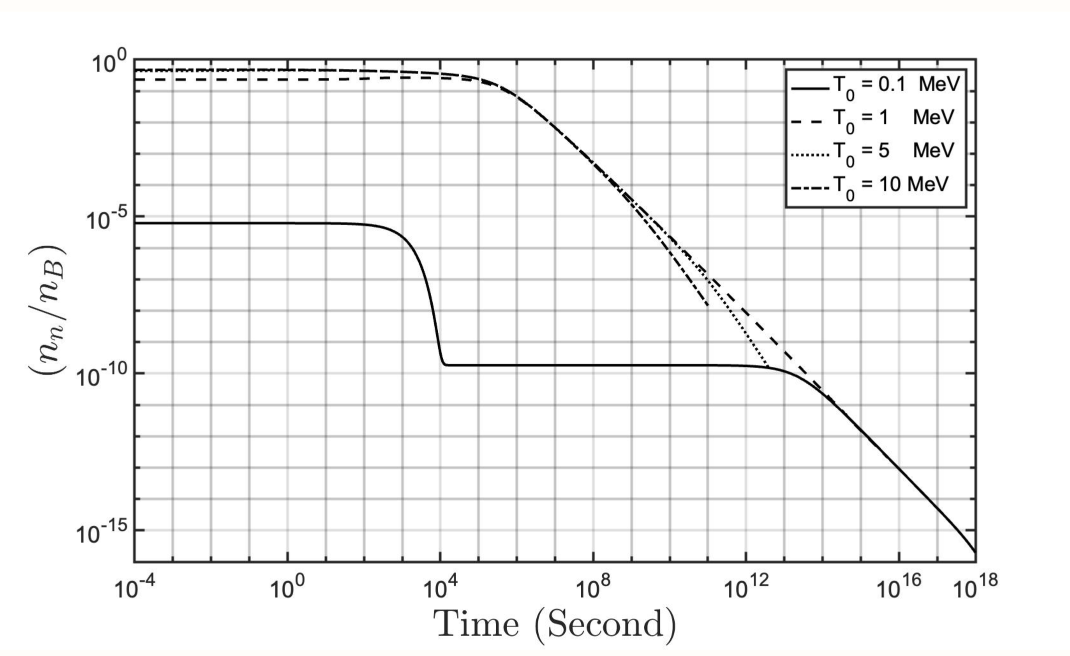

Figure 2: The time evolution of the abundance neutrons in the region at different initial temperatures.

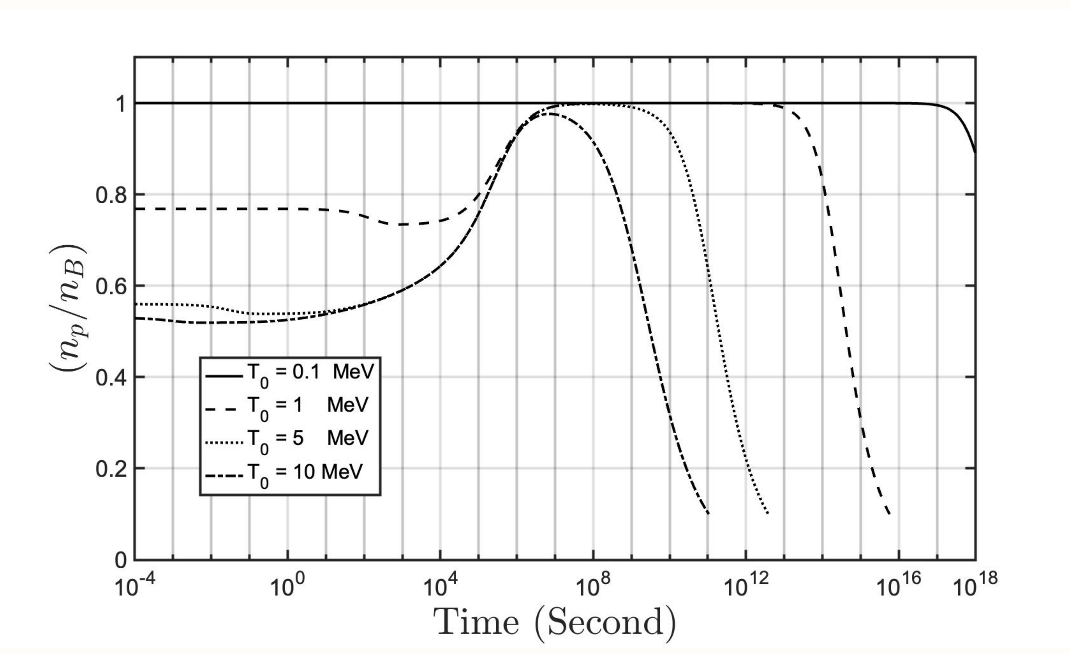

Figure 3: The time evolution of the abundance protons in the region at different initial temperatures.

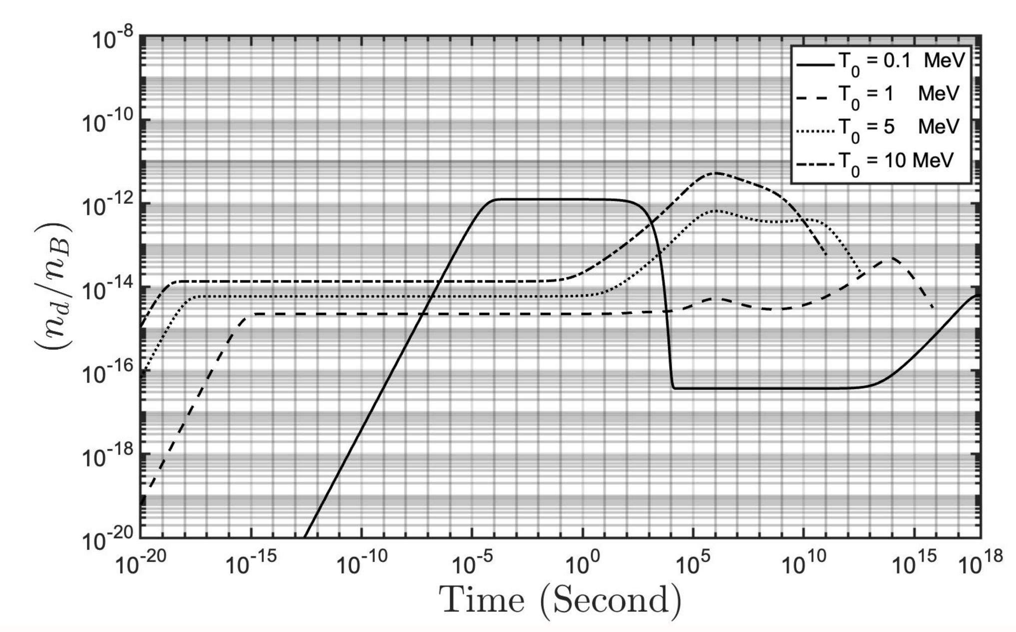

Figure 4: The time evolution of the abundance ratio (n_d/n_B) in the region at different initial temperatures.

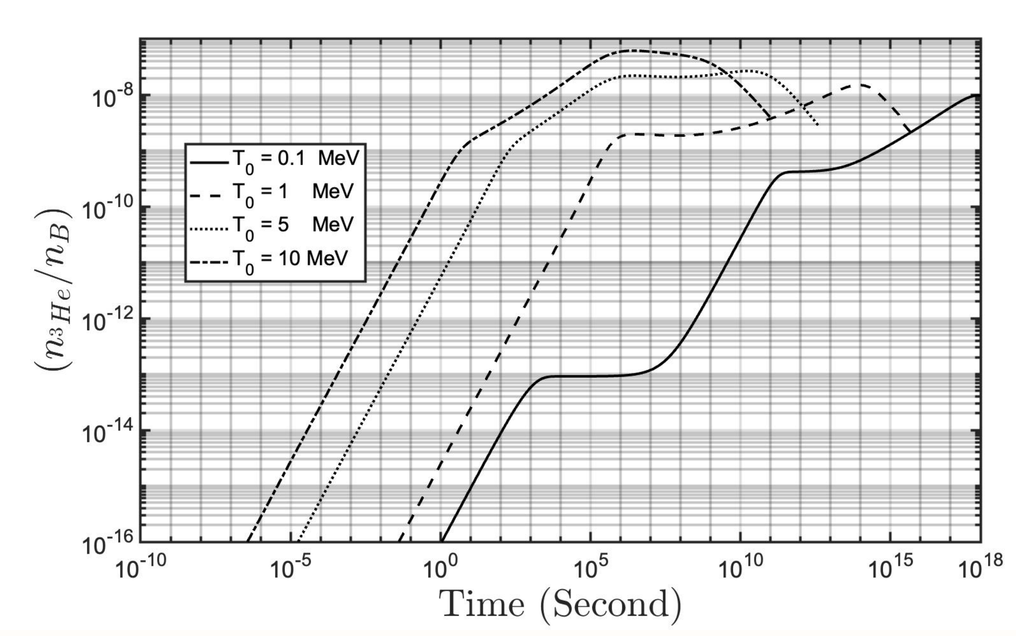

Figure 5: The time evolution of the abundance ratio $(n_{{}^3He}/n_B)$ in the region at different initial temperatures.

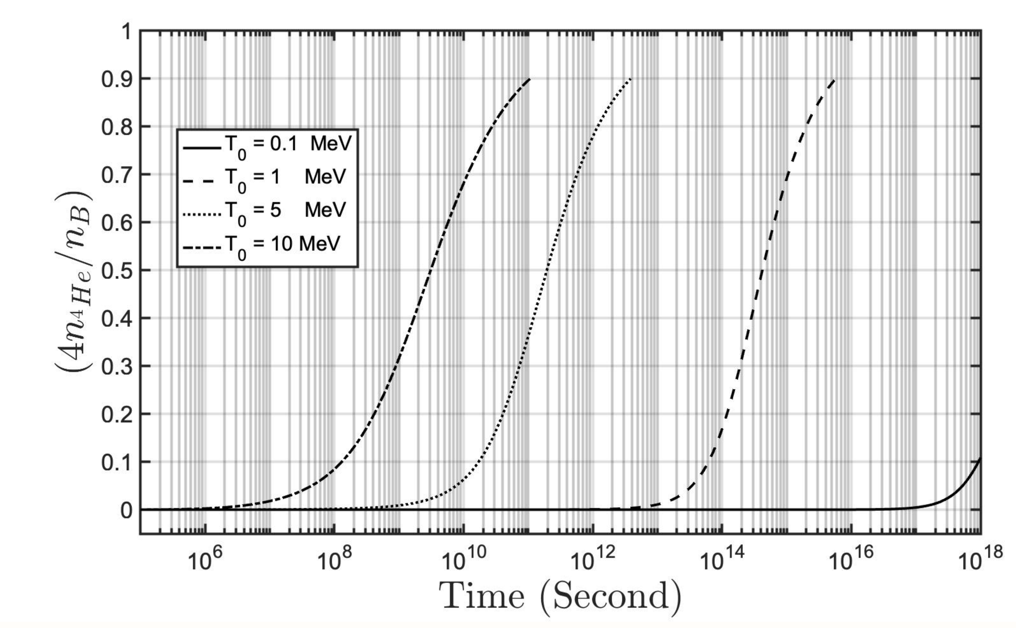

Figure 6: The time evolution of the density ratio $\rho_{{}^4He}/\rho_B = 4n_{{}^4He}/n_B$ in the region at different initial temperatures log-linear scale.

Summary and conclusions

We considered the thermonuclear reaction rates due to effects of electron-positron annihilation, reactions of weak proton-neutron transitions, and the production of light nuclides during the early stages of the universe. It is shown that the major neutrino production channel is electron-positron annihilation at higher temperatures, which is dominant in comparison to other thermonuclear reaction rates. However, the reaction rates slow down as the region cools down due to threshold effects, a drop in neutron concentrations, and electron-positron annihilation. Furthermore, a region with an anomalous chemical composition formed.

References

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