Investigation of neutrino cooling effect of primordial hot areas in dependence on its size

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Introduction

- We study a piece of hot primordial matter of the early Universe, where some reactions $p \leftrightarrow n$, producing ν, can proceed. its mass $10^4 - 10^8 M_\odot$.
- we assume that the baryonic matter was captured by the gravitational forces, when it was hot in the early universe and can be heated or cool down before the star formation.
- This region does not expand, has a finite size "1ps" and temperature $T \sim$ keV $-$ MeV, as it was obtain in our previous work (we need to investigate more).
- This region will be transparent for neutrinos in dependence from its size, that will be shown here. Neutrinos are produced due to reactions of $p \leftrightarrow n$ transition.
- This region is big enough not to lose photons. Characteristic time of photon escaping the cluster is bigger than the modern Universe age.
- such regions can be formed like primordial black hole cluster (as we considered in previous work).

Reactions inside heated area

- The basic reactions of neutrino production are supposed to be the following

$$e^- + p \to n + \nu_e, \tag{1}$$

$$e^+ + n \to p + \bar{\nu}_e, \tag{2}$$

$$e^+ + e^- \to \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau}, \tag{3}$$

$$n \to p + e^- + \bar{\nu}_e. \tag{4}$$

- We consider $T \sim 100$ keV. Nuclear reactions can go. It leads to neutrino production which cool down the matter inside the cluster.

Reactions inside heated area

Given reactions are as follows. The neutrino production rate per unit volume, $\gamma_i \equiv \Gamma_i/V$, for each reaction are respectively

$$\gamma_{en} = n_{e^+} n_n \sigma_{en} v, \tag{5}$$

$$\gamma_{ep} = n_{e^-} n_p \sigma_{ep} v, \tag{6}$$

$$\gamma_{ee} = n_{e^-} n_{e^+} \sigma_{ee} v, \tag{7}$$

$$\gamma_n = \frac{n_n}{\tau_n}. \tag{8}$$

Reactions inside heated area

The cross sections formulas

$$\sigma_{en} = \sigma_{ee} = \sigma_w \sim G_{\mathrm{F}}^2 T^2, \tag{9}$$

$$\sigma_{ep} = \sigma_w \exp\left(-\frac{Q}{T}\right), \tag{10}$$

$Q = m_n - (m_e + m_p) = 0.77$ MeV , G_{F} is the Fermi constant.

Reactions inside heated area

The number densities formulas

$$n_p = \frac{n_B}{1+\exp\left(-\frac{\Delta m}{T}\right)}, \qquad n_n = n_p(T)\exp\left(-\frac{\Delta m}{T}\right), \tag{11}$$

$$n_{e^-} = n_e^{eq}(T) + \Delta n_e, \qquad n_{e^+} = n_e^{eq}(T)\exp\left(-\frac{m_e}{T}\right), \tag{12}$$

$$n_B \equiv n_p + n_n = g_B\,\eta n_\gamma(T_0), \qquad \Delta n_e \equiv n_{e^-} - n_{e^+} = n_p. \tag{13}$$

$\Delta m = m_n - m_p = 1.2$ MeV, $\eta = n_B/n_\gamma \approx 0.6 \cdot 10^{-9}$ is the baryon to photon relation in the modern Universe, $g_B \sim 1$ is the correction factors of that relation due to entropy re-distribution, $n_\gamma(T) = \frac{2\zeta(3)}{\pi^2}T^3$ and $n_e^{eq} = \frac{3\zeta(3)}{2\pi^2}T^3$

Temperature evolution

The first law of thermodynamics

$$\Delta Q = \delta U.$$

ΔQ and δU are the heat outflow due to neutrinos and inner energy of the matter inside cluster respectively. One writes them

$$-(\gamma_{en} + \gamma_{ep} + \gamma_{ee} + \gamma_{n}) E_{\nu} dt = 4bT^{3} dT, \tag{14}$$

E_{ν} is the energy of outgoing neutrino, b is the radiation constant.

Temperature evolution

Integrating Eq(14), one can get time dependence of the temperature in an implicit form

$$\Delta t = -4b \int_{T_0}^{T} \frac{T'^2 dT'}{\gamma_{en} + \gamma_{ep} + \gamma_{ee} + \gamma_n}. \quad (15)$$

Here explicit dependence of the functions γ_i on T is the following:
$\gamma_{en} = C_1 \cdot T^5 \exp\left(-\frac{Q}{T}\right)$, $\gamma_{ep} = C_2 \cdot T^5 \exp\left(-\frac{m_e + \Delta m}{T}\right)$,
$\gamma_{ee} = C_3 \cdot T^8 \exp\left(-\frac{m_e}{T}\right)$, $\gamma_n = C_4 \cdot \exp\left(-\frac{\Delta m}{T}\right)$, where exact view of C_i follows from Eqs.(5)–(10). The coefficients $C_{1,2,4}$ also contain the multiplier $\left[1 + \exp\left(-\frac{\Delta m}{T}\right)\right]^{-1}$.

Evolution of T from time for different initial temperature T_0 is shown in the figure

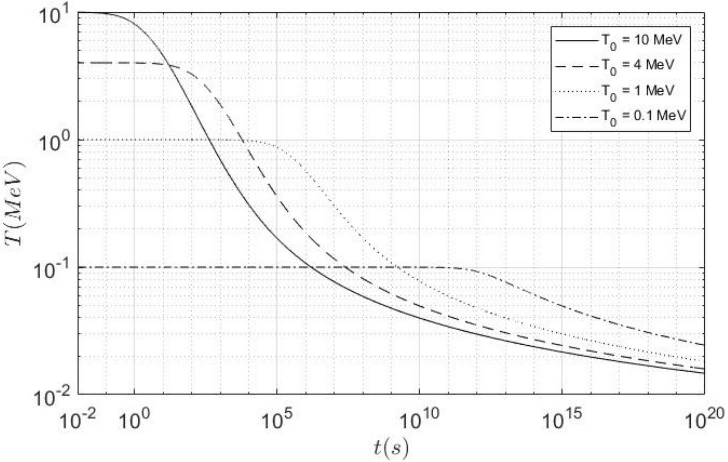

Fig (1): The time behaviour of the temperature inside the heated area.

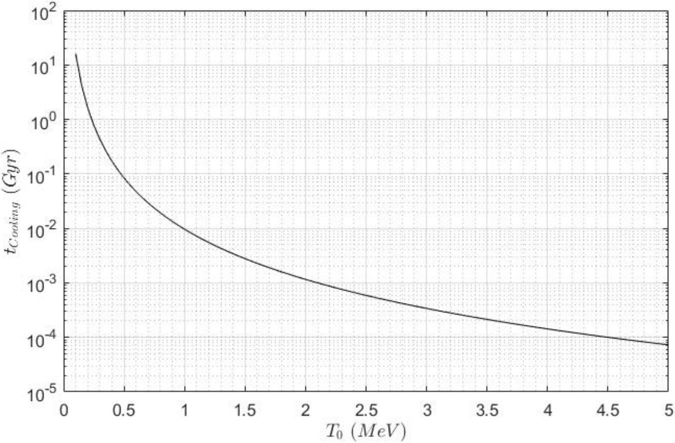

Fig (2): Cooling time t_{cooling} of media inside the heated area depending on the initial temperature T_0.

Time of escaping

The escape time of neutrinos from the region would be

$$t \sim \frac{R^2}{D} \sim R^2 \cdot G_F^2 \cdot T^5 \tag{16}$$

R is the size of cluster (diffusion) and D is diffusion coefficient $D = \frac{\lambda_\nu \cdot c}{3}$. where the neutrino mean free path is $\lambda_\nu = \frac{1}{n_e \cdot \sigma_\nu}$, neutrino has a very small interaction cross section: $\sigma_\nu \approx G_F^2 \cdot T^2$ and $n_e \approx \frac{3\zeta(3)}{2\pi^2} \cdot T^3$ is the electron number density.

Time of escaping

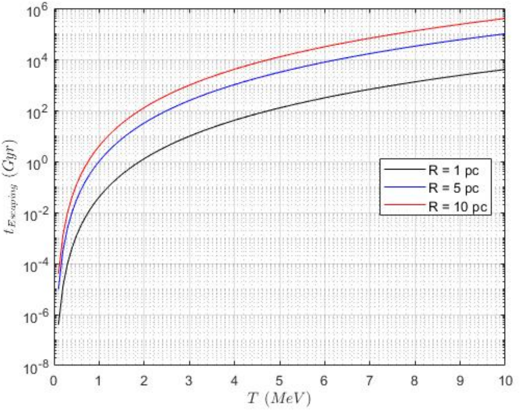

Fig (3):The relation between escaping time of neutrino and temperature of cluster.

Conclusion

- We show that the final temperature of such region is $\sim 10\,\mathrm{keV}$ provided that the initial temperature is within the interval $10\,\mathrm{keV}...100\,\mathrm{MeV}$.
- Neutrino cooling is realized due to reactions of weak $p \leftrightarrow n$ transitions.
- As one can see that even for $R \ll 1$ pc diffusion time is much bigger than the Universe lifetime.

Thank you for your attention.