Entropy production scenarios within SM and BSM Physics

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Abstract

The possible entropy production scenarios in the early universe are revisited. From the particle physics viewpoint we consider electroweak phase transition (EWPT) in the standard model (SM) and beyond standard model (BSM) scenarios like 2 Higgs doublet model (2HDM) as a source of entropy influx into the primordial plasma. First order phase transition in the case of 2HDM is realised. From a cosmological viewpoint the evaporation of mini primordial black holes (PBH) in their matter dominated (MD) stage in the early Universe is considered for the same. The production of entropy and in turn the dilution of preexisting baryon asymmetry and the dark matter density are considered in details as well as possible production of entropy as a result of first order phase transition is discussed qualitatively.

1. Introduction

- The thermodynamic quantity, entropy → measure of disorder, chaos or randomness.
- In the early universe, during the course of expansion when the primeval plasma was in thermal equilibrium, the entropy density was conserved.

$$S = \frac{\mathcal{P}+\rho}{T} a^3 = const. \qquad (1)$$

where $\mathcal{P}$ and ρ are the pressure and energy density of the plasma, $a(t)$ is the cosmological scale factor and $T(t)$ is the temperature of the plasma.

- Even though the early universe is associated with thermal equilibrium and entropy conservation, there can be several instances of non-conservation of entropy.
- Electroweak phase transition (EWPT) from symmetric to asymmetric phase during universe cooling.
- Primordial black hole (PBH) evaporation in the matter dominated (MD) stage can pour a significant amount of entropy into the plasma.
- QCD phase transition at $T \sim 150$ MeV.
- Dark matter freeze-out.

2. EWPT and entropy release in Standard Model (SM)

Consider the Lagrangian of theory in the following slightly simplified form:

$$\mathcal{L} = \frac{1}{2} g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - U_\phi(\phi) + \sum_j i\left[g^{\mu\nu}\partial_\mu\chi_j^\dagger\partial_\nu\chi_j - U_j(\chi_j)\right] + \mathcal{L}_{int}, \qquad (2)$$

where ϕ → the Higgs field with potential $U_\phi(\phi)$, $g_{\mu\nu} = (+,-,-,-)$ → signature of the metric with μ & ν → $0-3$..
The interaction Lagrangian is:

$$\mathcal{L}_{int} = \phi \sum_j g_j \chi_j^\dagger \chi_j. \qquad (3)$$

The summation is made over all relevant fields χ_j. The self-potential of ϕ with the temperature corrections can be written as:

$$U_\phi(\phi) = \frac{\lambda}{4}(\phi^2 - \eta^2)^2 + \frac{T^2\phi^2}{2}\sum_j h_j\left(\frac{m_j(T)}{T}\right), \qquad (4)$$

Here $\eta = 246\ GeV$ → vacuum expectation value of ϕ
$\lambda = 0.13$ → self-coupling of ϕ
T is the plasma temperature and $m_j(T)$ is the mass of the χ_j-particle at temperature T.
The last term appears due to the thermal corrections.

- The last temperature dependent term in eq. (4) appears as a result of thermal averaging of the interaction (3). It includes the contributions of ϕ itself and of all particles χ_j.
- The summation is made over all the particles and the functions $h_j(m_j/T)$ are positive.
- At high temperatures, $T > m_j(T)$, it is multiplied by a constant factor. At low temperatures, $T < m_j(T)$, the function $h_j(m_j/T)$ is exponentially suppressed, $\sim \exp[-m_j(T)/T]$.

We are mostly interested in the contribution of fermions. Their Yukawa coupling constants to the Higgs field are determined by their masses at zero temperature, $m_f = g_f\eta$.

- The masses of all particles depend on the temperature, $m_j = m_j(T)$, because the masses are proportional to the expectation value of the Higgs field and the latter is proportional to the temperature dependent value of ϕ at the minimum of the potential (4):

$$\phi^2_{min}(T) = \eta^2 - (T^2/\lambda)\sum_j h_j\left(\frac{m_j(T)}{T}\right) \qquad (5)$$

And correspondingly,

$$m_f^2(T) = g_f^2\phi^2_{min}(T) = g_f^2\left[\eta^2 - (T^2/\lambda)\sum_j h_j\left(\frac{m_j(T)}{T}\right)\right]. \qquad (6)$$

Here $j = f$ is the index of χ_f-particle which acquires mass through a non-zero expectation value of ϕ. The summation in the r.h.s. of this equation is made over all particles, χ_j and ϕ.

- The oscillations of ϕ around ϕ_{min} are quickly damped and hence we take $\dot\phi = \dot\phi_{min}$ and neglect $\ddot\phi^2$ because the evolution of ϕ_{min} is induced by the universe expansion which is quite slow.
- In the range from GeV to keV scale, we find the total amount of entropy is increased by 13%.. This result is based on [1].
- In the extended versions of electroweak theory, for example, 2HDM or other theories with several Higgs fields, the entropy release maybe considerably larger.

3. EWPT and entropy release in 2HDM

This part of the work is based on [2].
We now move to the minimal extension of the SM, namely Two Higgs Doublet Model (2HDM). The lagrangian density in 2HDM is given as:

$$\mathcal{L} = \mathcal{L}_f + \mathcal{L}_{Yuk} + \mathcal{L}_{gauge,kin.} + \mathcal{L}_{Higgs}. \qquad (7)$$

The individual terms are the **Fermionic Lagrangian, Yukawa Term, Gauge Kinetic Terms and the Higgs Terms** respectively.
The **Fourth Term** is defined as:

$$\mathcal{L}_{Higgs} = (D^\mu\Phi_1)^\dagger(D_\mu\Phi_2) + (D^\mu\Phi_1)^\dagger(D_\mu\Phi_2) - V_{tot}(\Phi_1,\Phi_2,T) \qquad (8)$$

where $V_{tot}(\Phi_1,\Phi_2,T)$ is the CP-conserving 2HDM potential. And the CP-conserving 2HDM potential looks like:

$$V_{tot}(\Phi_1,\Phi_2,T) = V_{tree}(\Phi_1,\Phi_2) + V_{CW}(\Phi_1,\Phi_2) + V_T(T). \qquad (9)$$

Here we have considered the real sector of type-I 2HDM.

When the temperature of the universe drops down to the critical temperature T_c, a second local minima appears at the same height of the global minima situated at

$$<\Phi_1> = <\Phi_2> = 0 \qquad (10)$$

The critical temperature can be obtained using the expression:

$$V_{tot}(\Phi_1 = 0, \Phi_2 = 0, T_c) = V_{tot}(\Phi_1 = v_1, \Phi_2 = v_2, T_c), \qquad (11)$$

where v_1, v_2 are the second minimas.

- We've assumed the same algorithm as that of the previous one, where the oscillations of the Higgs fields around minimum after it appeared in the course of the phase transition are damped due to particle production by the oscillating field.
- But unlike the previous section, analytical calculations were not possible and hence we treated the problem numerically.
- BSMPT is a C++ package which deals with various properties and features related to 2HDM and baryon asymmetry. In this case, the package was used to calculate the critical temperature T_c and the vacuum expectation value VEV and the effective potential V_{eff} for each benchmark points.

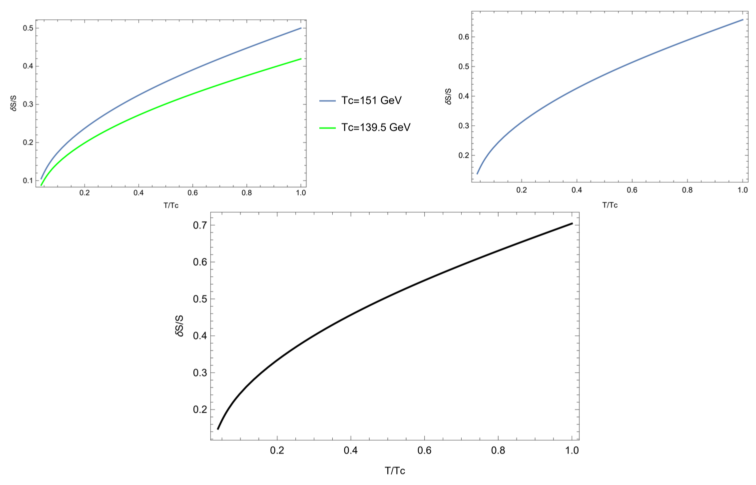

Figure 1: *The entropy release for four different scenarios are shown above. The left panel shows the entropy production for T_c = 139.5 GeV and 151 GeV. The right panel shows the entropy production for T_c = 173.5 GeV (blue line) and the bottom panel shows the entropy production for T_c = 255.5 GeV (black line).*

- As seen from the figures, the entropy production is considerably higher compared to the standard model scenario. The entropy production for $T_c = 139.5\ GeV \sim 41\%$ and so on, much higher than the SM scenario.
- This entropy release due to the EWPT can considerably reduce the abundance of frozen out dark matter present in the universe before EWPT.

4. PBH evaporation as a source of entropy production

Sufficiently light primordial black holes (PBH) could evaporate in the very early universe resulting in huge amount of entropy production and dilute the pre-existing baryon asymmetry and/or the frozen density of stable relics. Some key points to note:

- We considered PBHs of small masses, such that they evaporated before BBN.
- They decayed before our time but they can have noticeable impact in the present.
- They can pour sufficient entropy into the plasma and diminish the pre-existing baryon asymmetry and diminish the relative (with respect to the relic photon background) density of dark matter particles.
- Baryon asymmetry could be generated due to PBH evaporation.
- Dark matter could also be created in this process.

But we neglect these processes and consider only dilution of baryons and dark matter particles by the PBH evaporation. And this reduction is calculated for 3 different scenarios.

- Delta function mass spectrum with instant decay approximation.
- Delta function mass spectrum with exact solution (instant decay is lifted).
- Extended mass spectrum.

To begin with, we consider here the simplest model of PBHs with fixed mass M_0 with the number density at the moment of creation:

$$\frac{dN_{BH}}{dM} = \mu_1^3\,\delta(M - M_0), \qquad (12)$$

where μ_1 is a constant parameter with dimension of mass. All the black holes were created at the same moment and the fraction of the PBH energy (mass) density at production was:

$$\frac{\rho_{BH}^{(in)}}{\rho_{rel}^{(in)}} = \epsilon \ll 1 \qquad (13)$$

As all the PBHs evaporated, entropy influx into the plasma took place and this in turn reduced the pre-existing baryon asymmetry and the dark matter density.

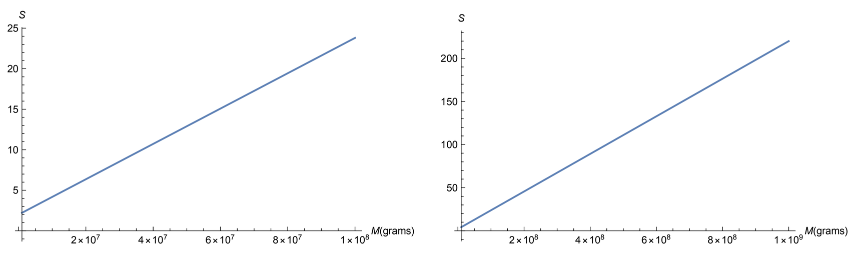

Figure 2: *Entropy suppression factor due to PBH decay in the instant decay approximation for larger masses up to maximal mass $M = 10^8$ g (left panel) and $M = 10^9$ g (right panel) as a function of BH mass for $\epsilon = 10^{-12}$.*

We relax the instant decay approximation and solve numerically equations describing evolution of the cosmological energy densities of non-relativistic PBHs and relativistic matter. We take a dimensionless time $\eta = t/\tau_{BH}$ and the equations can be written as:

$$\frac{d\rho_{BH}}{d\eta} = -(3H\tau + 1)\rho_{BH} \quad (14)$$

$$\frac{d\rho_{rel}}{d\eta} = -4H\tau\rho_{rel} + \rho_{BH}. \quad (15)$$

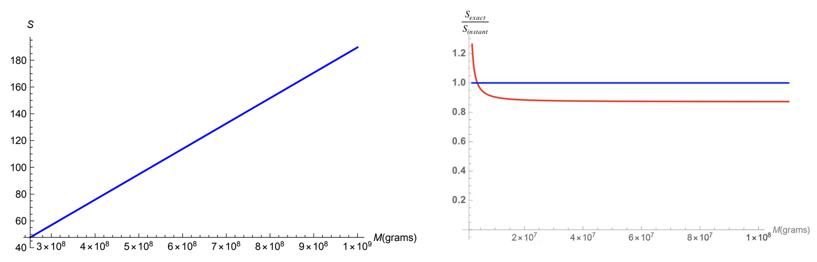

Figure 3: *The entropy suppression factor as a function of mass is shown in the left panel. The ratio of the entropy suppression factor of the exact fixed mass calculations (red) to the instant decay and change of the expansion regime approximation. The blue line describes the hypothetical ratio equal to unity is shown in the left panel. $\epsilon = 10^{-12}$ in both cases.*

The extended mass function has the following form:

$$\frac{dN_{BH}}{dM} = f(M,t), \quad (16)$$

where N_{BH} is the number density of PBH.
We consider a couple of illustrative examples in what follows, assuming that the function

$$F(x) = \epsilon(M)/z(\eta_f(M)) \quad (17)$$

is confined between $x_{min} = (M_{min}/M_0)$ and $x_{max} = (M_{max}/M_0)$. We take 2 examples of $F(x)$

- $F_1(x) = \epsilon_0/(x_{max} - x_{min})$ for $x_{min} < x < x_{max}$ and $F_1 = 0$ for x outside of this interval. Evidently $x = 1$ should be inside this interval.
- $F_2(x) = \frac{\epsilon_0}{N} a^2 b^2 (1/a - 1/x)^2 (1/x - 1/b)^2$. Here N is the normalization factor, chosen such that the maximum value of $F_2/\epsilon = 1$.

F_2 can be quite close numerically to the log-normal distribution with a proper choice of parameters.

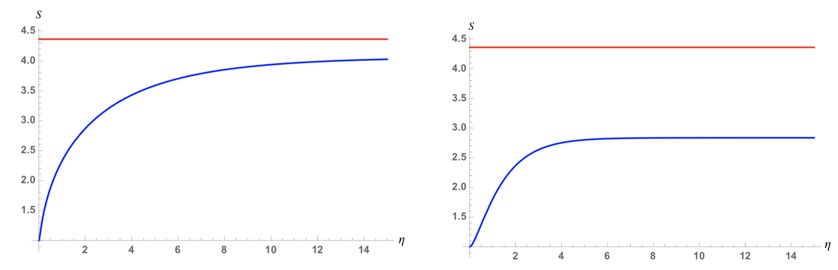

Figure 4: *The temporal evolution of entropy suppression for flat mass spectrum $F_1(x)$, $M_{BH} = 10^7$ g and $\epsilon = 10^{-12}$ as a function of dimensionless time η for $M_0 = 10^7$ g, $a = 1/3$, and $b = 4/3$ (blue) is shown in the left panel. The same for $F_2(x)$ is shown in the right panel. Red line is the entropy suppression factor approximately calculated in the instant approximation.*

- As it is shown here, the suppression of thermal relic density or of the cosmological baryon asymmetry may be significant if they were generated prior to PBH evaporation. This might also lead to subsequent lepton asymmetry, thus resulting in lepto-thru-baryogenesis.
- This phenomenon can lead to the production of the dark matter particles but with the present parameters it can be shown that the amount of dark matter produced is negligible and does not effect the entropy production. Or in other words, the stable supersymmetric relics produced in the process of PBH evaporation would make negligible contribution to the density of dark matter.

This part of the work is based on [3].

5. Acknowledgement

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