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Leptogenesis via absorption by primordial black holes

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Recently a new baryogenesis mechanism proceeding via different particle and antiparticle capture rates by primordial black holes was suggested. Such a difference could appear due to interference between tree and one-loop scattering diagrams. The baryon number could be conserved at the particle interaction level. In present work the analogous leptogenesis mechanism is considered instead. The lepton asymmetry can be transferred into baryon sector through the electroweak processes that break both baryonic and leptonic numbers conservation but conserve $B - L$.

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1. Introduction

Baryon asymmetry of the Universe (BAU) represents one of major hints towards a Standard Model (SM) extension. Primordial light element abundances and relic photons temperature anisotropies observations confine its magnitude to [1]

$$\eta_b \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.14 \pm 0.19) \times 10^{-10}. \tag{1}$$

BAU existence can be explained via particles interactions if three Sakharov conditions are satisfied [2]

- B-number is not conserved
- C and CP symmetries are violated (CPV)
- Processes are out of thermal equilibrium rates

B- and L-numbers are not conserved in the SM along with CPV presence, the former especially takes place at temperatures $T \gtrsim 160\,\mathrm{GeV}$. However, the third Sakharov condition is not satisfied in the case of the second order phase transition. Still, the B/L numbers non-conservation feature is fundamental for a class of baryogenesis mechanisms based on preceding lepton asymmetry transfer into baryon sector by means of SM non-perturbative processes.

The list of relevant mechanisms can be expanded if there are black holes in the early Universe (PBHs). They could be formed from big enough energy density contrasts $\delta\rho/\rho \gtrsim 0.4$ [3]. Even though it is hard to determine primordial origin of black hole (however, see [4]) the recent JWST discoveries of high redshift galaxies hosting a black hole in their core put a pressure on ΛCDM model while making PBHs seeding galaxies formation a compelling model.

PBHs participation in baryogenesis processes is also studied and several interesting mechanism are found [5–7]. Usually, the **Hawking radiation** is considered either symmetric (incorporating particles with specific properties) or asymmetric (in presence of chemical potential associated with relevant particles). A brief review of an alternative mechanism operating via different absorption rates of particles and antiparticles is provided in Section 2. Then a rough asymmetry evaluation based on accretion picture is given.

2. Asymmetric capture mechanism

Recently a new mechanism was proposed [8] based on absorption rates difference. An illustrative example is black hole charging in cosmic plasma consisting of protons and electrons [9]. Due to large mass difference $m_p/m_e \sim 10^3$ they have different fluid velocities. Then amounts of absorbed electrons and protons differ so black hole obtains electric charge.

Considered mechanism incorporates C and CP symmetries violation for particles and antiparticles carrying baryonic (leptonic) charge as a source of mobility difference. Such CPV comes from a tree and triangular one-loop diagrams interference and by order of magnitude is

$$\varepsilon' = \frac{\sigma(X + a \to X + c) - \sigma(\bar{X} + a \to \bar{X} + c)}{\sigma(X + a \to X + c) + \sigma(\bar{X} + a \to \bar{X} + c)} \sim f^2 \tag{2}$$

with coupling constant f. Then fluid velocities difference is estimated through averaged velocity as $v_- \simeq \varepsilon' v_{av}$. Such difference gives rise to baryon number per PBH $N_B \approx 4\pi r^2 v_- t_H n_X$. Produced asymmetry should be further integrated over the PBH mass spectrum. In aforementioned article light PBHs are considered being already evaporated. Consequently they dilute entropy density

$$s = \frac{\rho + \mathcal{P}}{T} = \frac{2\pi^2}{45} g_*(T) T^3 \tag{3}$$

by a factor $S \sim 10^5 \epsilon M/\text{grams}$ [10]. Here ρ is energy density, $\mathcal{P}$ is pressure, and g_* is effective number of relativistic degrees of freedom being $g_*(T > 160\,\text{GeV}) = 106.75$ within the SM. It was concluded that the mechanism is able to provide asymmetry at the level of BAU.

2.1 Motion in the early Universe

Fluid particle motion in the early Universe in presence of gravitational source and friction in Newtonian limit $r_g \ll r \ll r_H \equiv 1/H$ is governed by equation:

$$\ddot{r} + \gamma \dot{r} + q H^2 r + \frac{r_g}{2r^2} = 0 \tag{4}$$

with collision frequency $\gamma \equiv \langle \sigma_{el} v_{\text{møl}} \rangle n_{rel}$, cosmological force $qH^2 r$ taken from [11], PBH Schwarzschild radius $r_g \equiv 2GM = GM/{m_{Pl}}^2$, and deceleration parameter

$$q \equiv -\frac{\ddot{a} a^2}{\dot{a}}. \tag{5}$$

This equation can be analytically integrated (without friction term) under $H \sim \text{const}$ approximation. Then a following solution can be constructed [12]

$$r(t) = r_{max} \cos^{2/3}(3Ht/2), \tag{6}$$

with $r_{max} = (r_H^2 r_g)^{1/3}$ determined by equilibrium between cosmological repulsion and gravitational attraction. However, this solution is accurate if capture time is $t_{cap} \ll t_H$. Otherwise, Hubble parameter change can become significant. Also, interpretation of force equilibrium point as maximum radius for absorption of particles is correct for $q < 0$. However in radiation-dominated Universe ($q = 1$) cosmological force acts inward thus only enhances accretion rates.

It is convenient to introduce dimensionless $x \equiv m_1/T$ and instead of time and radial coordinate consider

$$\begin{cases} t = \frac{x^2}{2m_*}, \\ r = \mathfrak{r} r_g, \end{cases} \tag{7}$$

with new mass scale determining Universe expansion during relevant times, $m_* = m_1^2/{m_{Pl}}^* = m_1^2/m_{Pl} \cdot \sqrt{90/8\pi^3 g_*(T)} \sim 7 \times 10^{17}$ GeV. Then equation (4) transforms into

$$x^2 \mathfrak{r}'' + \left(\frac{\gamma}{m_*} x^3 - 2x \right) \mathfrak{r}' + \mathfrak{r} + \left(\frac{x}{x_a} \right)^4 \frac{1}{2\mathfrak{r}^2} = 0. \tag{8}$$

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First, collision frequency estimated as $\gamma x^3/m_* \approx 0.12 g_* f^4 m_{Pl}{}^*/m_1 = \mathrm{Const}$ can be treated perturbatively if small enough. Then equation can further be simplified by $x = \xi^\alpha$, $\iota = \xi^{(3\alpha+1)/2} w$ substitution resulting in Emden-Fowler-type equation

$$w'' = A\frac{\xi^{-(1+\alpha)/2}}{w^2}, \quad A = -(10\xi_a^{4\alpha})^{-1}. \tag{9}$$

This particular equation seems to have no exact solution in quadratures. In what follows a numerical solution is used.

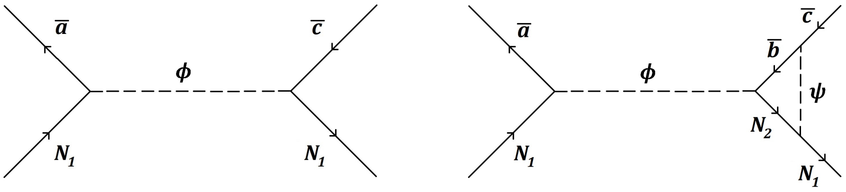

Figure 1: Feynman diagrams whose interference give rise to C and CP symmetries violation.

2.2 Particle's model

A minimal lagrangian satisfying necessary conditions was suggested in [13]

$$\mathcal{L}_{int} = -g_{\bar{a}X}\bar{\phi}\bar{a}X - g_{\bar{c}X}\bar{\phi}\bar{c}X - g_{\bar{b}Y}\bar{\phi}\bar{b}Y - g_{\bar{Y}X}\psi\bar{Y}X - g_{\bar{b}a}\psi\bar{b}a - g_{\bar{b}c}\psi\bar{b}c + \text{h.c.} \tag{10}$$

with added X, Y, b heavy fermions, scalar fields ψ, ϕ, and SM particles a, c. Complex coupling constants are required to allow C and CP violation. In what follows a leptogenesis mechanism will be considered instead thus X, Y particles will be denoted as leptons N_1, N_2. Then CPV comes from the interference between diagrams shown in Figure 1. The authors calculate CPV magnitude by means of Cutkosky cutting rules and found an additional factor to previously made estimation

$$\varepsilon' = \frac{\mathrm{Im}\{g_{c1} g_{12}^* g_{b2}^* g_{bc}\}}{|g_{a1}|^2}\mathrm{Im}\{\mathcal{I}\} \approx \frac{f^2}{2\sqrt{\pi}x^{3/2}} \tag{11}$$

with $\mathcal{I}$ denoting a loop integral.

3. Towards accretion

Consider amount of particles contained in differential volume between some r and $r + \delta r$,

$$\delta N = 4\pi r^2 n_1 \delta r = 4\pi r_g^3 n_1 \iota^2 \frac{\delta \iota}{\delta x}\delta x. \tag{12}$$

At the moment x PBH absorbs particles from initial distance $\iota_0 = 1/f(x)$ if their trajectory can be expressed as $\iota = \iota_0 f(x)$. Hence absorption rate can be estimated as

$$\Gamma_{abs1}(x) = \frac{\delta N/\delta x}{n_1(x)} = 4\pi r_g^3 \iota_0^2(x) v(\iota_0, x) = 4\pi r_g^3 \frac{f'(x)}{f^3(x)} \tag{13}$$

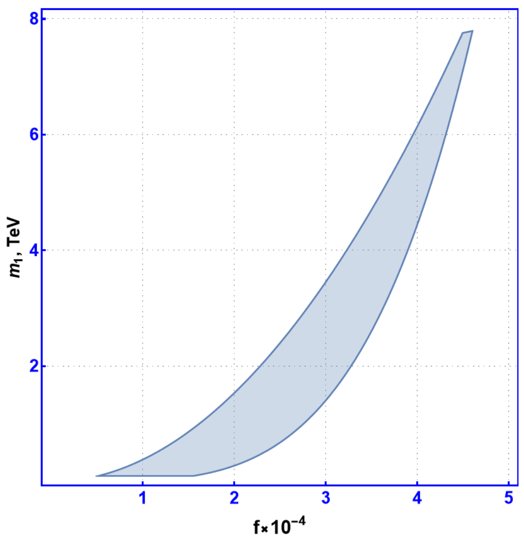

Figure 2: Coupling constant f and mass m_1 parameter space satisfying inequalities (17), (18)

with $f(x)$ constructed from numerical solution of equation of motion.

Next, the found quantity should be integrated over the PBHs mass spectrum. For the sake of estimation the monochromatic one is used simplifying total absorption rates to

$$\Gamma_{abs}(x) = \Gamma_{abs1} n_{PBH} = 3.33\epsilon \left(\frac{x_a}{x}\right)^3 \frac{f'(x)}{f(x)} \tag{14}$$

with $\epsilon \equiv \rho_{PBH}/\rho_{rel} \ll 1$ at the moment of PBHs appearance x_a.

Suggesting N_1 partcles to be (almost) stable so they can preserve their number density the following Boltzmann equations can be considered

$$\begin{aligned} \partial_x Y &= -\Gamma_{abs} Y - \Gamma_{ann}(Y^2 - Y_{eq}^2), \\ \partial_x \bar{Y} &= -\Gamma_{abs} \bar{Y} - \Gamma_{ann}(\bar{Y}^2 - Y_{eq}^2), \end{aligned} \tag{15}$$

with introduced yield $Y \equiv n/s$ normalized to entropy density thus $Y_{eq} \approx 0.14 g_1/g_* \cdot x^{3/2} e^{-x}$. Also, proper value of (1) should be considered, $\Delta_{Y_B} = (8.75 \pm 0.23) \times 10^{-11}$. Note, that cosmological expansion term is absent due to the choice of $(x, y \equiv p/T)$ variables instead of (t, p), hence annihilation rate is slightly differently defined:

$$\Gamma_{ann} = \Gamma'_{ann} \frac{s}{Hx} = \frac{2\pi^2 g_*}{45} \frac{f^4}{x^3} \frac{m_{Pl}{}^*}{m_1}. \tag{16}$$

Once annihilation processes rates are slower than the Hubble parameter, $\Gamma'_{ann} < H$, particle's number density in comoving volume is conserved. It can be relativistic if in inequality

$$g_1 \frac{3 \times 10^{13}\text{GeV}}{m_1} \left(\frac{f}{0.04}\right) < x_f \tag{17}$$

x_f can reach unity. However, the transformation of the asymmetry into the SM sector scattering cross-section requires

$$g_* \frac{3 \times 10^{13}\text{GeV}}{m_1} \left(\frac{f}{0.04}\right) > x_{EW} \equiv \frac{m_1}{T_{EW}}. \tag{18}$$

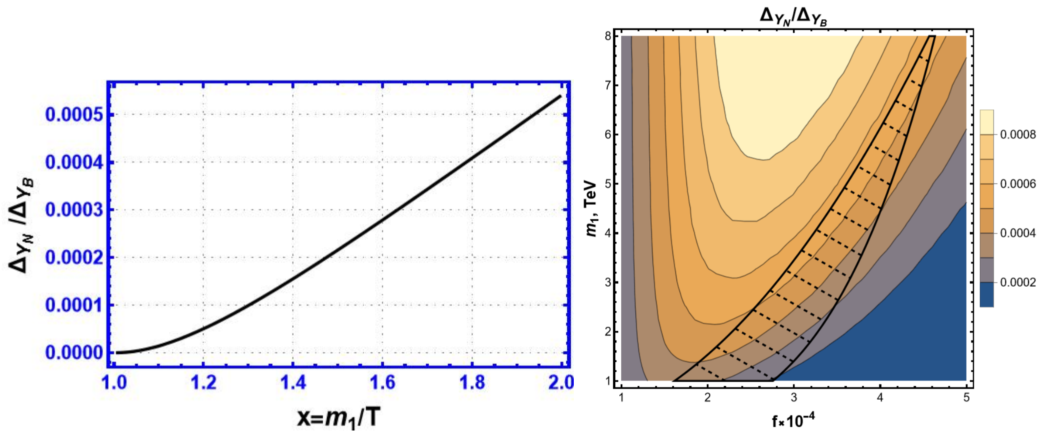

Figure 3: Produced asymmetry Δ_{Y_N} normalized to BAU value Δ_{Y_B} resulting value (right figure) and evolution for $m = 3.4 \times 10^3$ GeV and $f = 10^{-4}$ (left figure).

PBH mass dependence on appearance time x_a and particle mass m_1 expressed in solar mass $M_\odot$ is

$$M \sim 4.8 \times 10^{-2} x_a^2 \left(\frac{\text{GeV}}{m_1}\right)^2 M_\odot, \tag{19}$$

if initially it is about horizon mass $M_{hor} = m_{Pl}{}^2 t$. According to parameter space of interest that depicted in Figure 2, such PBHs can have mass about of asteroid and be presented in Universe today.

Also, Schwarzschild radius should be larger than particle's wavelength thus $x_a > \sqrt{2m/m_{Pl}}^*$. Finally, particle motion is determined by sources located with the cosmological horizon. At some moment there will be likely more than one PBH and motion, in general, become more sophisticated. Thus we determine applicability of single-PBH accretion regime as

$$x \lesssim \left(\frac{\pi^4}{90\zeta(3)\epsilon}\right)^{1/3} x_a, \tag{20}$$

and final asymmetry is provided once this expression turns into equality.

With parameters space being discussed we consider $\Delta_{Y_N} \equiv Y - \bar{Y}$ and $Y_{av} = (Y + \bar{Y})/2$ so equations transform to

$$\begin{aligned} \frac{dY_{av}}{dx} &= -\Gamma_{abs} Y_{av} - \Gamma_{ann}(Y_{av}^2 - Y_{eq}^2), \\ \frac{d\Delta_{Y_N}}{dx} &= \delta\Gamma_{abs} Y_{av} - \Gamma_{abs}\Delta_{Y_N} - 2\Gamma_{ann}\Delta_{Y_N} Y_{av}. \end{aligned} \tag{21}$$

Numerical solution is provided in Figure 3 for $x_a = 0.1$, $\epsilon \sim 10^{-4}$. Even though chosen ϵ value exceeds realistic one ($\epsilon < 10^{-7}$) it arguably does not change the result that such model cannot quantitatively explain observed BAU.

4. Conclusions

Baryogenesis mechanism operating through particles capture by PBH is a promising yet far from being completely explored scenario. One of advantages is to exploit opportunity to conserve appropriate number $B, L, B-L$, etc. and do not necessarily went out of equilibrium rates.

Motion in the early Universe is influenced by cosmological force that depends on the expansion regime, i.e. sign of deceleration parameter q. It acts as inward force during radiation-dominated stage of evolution therefore enhancing accretion rates. It is shown that without friction term equation of motion can be reduced to the Emden-Fowler-type equation that has no exact solution.

Minimal model results in additional factor to the coupling constant square proportional to $x^{-3/2}$ making prolonged realization less efficient. However, other physical models can lead to different results.

Simple estimation of leptogenesis with TeV-scale leptons that release their asymmetry through scattering processes shows no significant produced asymmetry.

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