Absorption from Primordial Black Holes as source of baryon asymmetry

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We propose a new mechanism for baryogenesis, in which baryon asymmetry is generated by absorption of a new particle $X$ carrying baryon number onto Primordial Black Holes (PBHs). Due to CP violation of $X$ and $X$ scattering with the plasma surrounding PBHs, the two conjugate particles are differently absorbed by PBHs, leading to the production of an asymmetry in the $X$ sector. The production is halted by PBH evaporation, after which the asymmetry is transferred into the baryonic sector via $X$ decay. We show that this mechanism can produce the correct amount of asymmetry without violating the known constraints on PBHs concentration. Furthermore, we provide a systematic study of the parameter space, identifying the regions leading to the production of the correct baryon asymmetry.

Introduction. Our universe exhibits an asymmetry among baryons and anti-baryons, whose origin is one of the fundamental problems of physics. The amount of baryon asymmetry can be quantified by the measured ratio $\eta_B^{\exp} = \frac{n_B - n_{\bar{B}}}{s_R} = (8.75 \pm 0.23) \cdot 10^{-11}$, where $n_B(n_{\bar{B}})$ is the baryon (anti-baryon) number density and $s_R$ is the entropy density. In 1967, Sakharov proposed three conditions [4] necessary for a viable baryogenesis mechanism: violation of the baryon number, violation of CP and C symmetries, and inequilibrium processes. While the Standard Model satisfies Sakharov conditions, it is not able to reproduce quantitatively the asymmetry [5–9]. Therefore, a number of extensions have been proposed to reproduce the correct asymmetry, including electroweak baryogenesis [10–12], baryogenesis via leptogenesis [13–15], GUT baryogenesis [16], and the Affleck-Dine mechanism [17]. In a novel framework proposed in Refs. [18, 19], baryon asymmetry is produced by the different absorption of particles and antiparticles of a new species $X$, carrying baryon number, onto a population of primordial black holes (PBH) [20, 21]. However, the quantitative value of the asymmetry is difficult to recover in this model. In fact, Ref. [19] suggests that strong absorption on PBHs is required to reproduce a large asymmetry, but a strong absorption over long timescales might lead to the complete absorption of both the particle and the antiparticle of the $X$ species, leading to a suppression of the asymmetry produced. In this work, we show that this problem can be solved by taking into account the evaporation of PBHs by means of Hawking radiation [22–25]. Evaporating PBHs have been well-studied in connection with baryon asymmetry generation [26–34] as well as with the dark matter problem [32, 35, 36] (see also [37–44]).

For PBH masses lighter than $10^9$ g, which is the range of interest for us, PBHs completely evaporate before the Big Bang Nucleosynthesis. The finite lifetime of PBHs due to evaporation provides a natural way of stopping the absorption before the species is completely depleted, thereby maintaining the asymmetry produced. A connected problem is that the remnant $X$ particles, being very massive, might dominate over radiation. In the model we propose here, this problem is solved by allowing the $X$ species to decay into baryons, accordingly transferring the asymmetry from the $X$ sector to the baryonic one. We show
that this mechanism can reproduce the correct asymmetry by explicitly solving the cosmological transport equations. Our results provide an effectively new mechanism for the production of the baryon asymmetry.

**The mechanism.** We introduce a particle $X$, together with its antiparticle $\overline{X}$, coupled to the Standard Model (hereafter denoted by $SM$) and endowed with baryon number $B_X$; we denote the mass of this particle by $m_X$ and its coupling in order of magnitude with the SM by $f$. For reference, we will assume the $X$ particles to be scalar: however, none of the results presented here should change in the assumption that it is a fermion. This particle is accreted by gravitational attraction onto a population of PBHs with mass $M$; the gravitational attraction is counterbalanced by the resistance due to collisions with the SM plasma surrounding the PBHs. Assuming that $X$ and $\overline{X}$ have slightly different cross-sections for scattering from the SM plasma, due to a small $C$ and CP violation, the absorption rate of $X$ and $\overline{X}$ within PBHs is different. The asymmetric absorption of $X$ and $\overline{X}$ leads to a continuous production of asymmetry in the $X$ sector. This production goes on until most of the PBHs evaporate due to Hawking radiation. The asymmetry can then be translated into the baryon sector by decaying into baryons and relativistic particles, so that the produced baryon asymmetry is

$$ \eta_B = B_X \frac{n_X - n_{\overline{X}}}{s_R}, \quad (1) $$

where $n_X$ ($n_{\overline{X}}$) is the $X$($\overline{X}$)'s number density, $B_X = 1$ is the baryon number of $X$, and $s$ is the entropy density. We now discuss quantitatively each of the necessary components for the determination of the final asymmetry.

**Absorption rate due to PBH.** The process of infalling of non-relativistic $X$ particles onto a PBH is determined by the balance between gravitational attraction and resistance induced by scattering with the SM plasma. We use the estimate of Ref. [19] for the rate of infalling of $X$ particles

$$ \frac{dN_X}{dt} = 4\pi G m_X n_X \frac{f(M)}{n_0 g \sigma_T^f T}, \quad (2) $$

where $G$ is Newton’s constant, $g \simeq 100$ is the number of relativistic interacting species in the plasma surrounding the PBH, $\sigma_T$ is the cross-section for scattering of $X$ particles with the SM, $n_0$ is the number density of each species in the plasma, $T$ is its temperature, and $n_X$ is the number density of $X$ particles. An equivalent expression can be obtained for $\overline{X}$. For the cross-section $\sigma_X$ we assume the unitarity bound $\sigma_X = f^4/m_X^2$. The cross-sections $\sigma_X$ and $\sigma_{\overline{X}}$ are slightly different due to CP violation: we assume $\sigma_X - \sigma_{\overline{X}} \simeq f^2 \sigma_X$ since the effect comes from the loop level [19]. Therefore, in the end we find

$$ \frac{d(N_X - N_{\overline{X}})}{dt} = 4\pi G m_X^3 n_X \frac{f(M)}{n_0 g \sigma_T^f T}. \quad (3) $$

While these relations hold for non-relativistic particles, we neglect absorption of relativistic particles: for this reason, we will determine the evolution of $X$ and $\overline{X}$ only after the species becomes non-relativistic.

**PBH evaporation.** PBHs are subjected to Hawking evaporation, emitting particles and gradually losing their mass. The evaporation rate is determined by the rate of emission of particles [45]

$$ \left( \frac{dM}{dt} \right)_{eva} = -5.34 \times 10^{25} \frac{f(M)}{M^2} \frac{g^3}{s^3} \text{s}^{-1}, \quad (4) $$

where $f(M)$ is a measure of the number of relativistic degrees of freedom emitted by the PBH, and is equal to 1 for $M \gg 10^{17}$. For the lighter PBHs studied $f(M)$ can be taken of order 10 without loss of generality. We note that as expected, for decreasing PBH masses more species are emitted and thus $f(M)$ increases [45]. If a population of PBHs are produced with an initial mass $M$, they will be completely evaporated by the time $t_e \simeq 6 \cdot 10^{-2} M_9^3 s$, where $M_9$ is the initial PBH mass expressed in grams. Using the time-temperature relation in a radiation-dominated Universe with a number of degrees of freedom for the energy density of order 100 we obtain the temperature of evaporation

$$ T_e \simeq 10^{10} \text{GeV} (M_9)^{-3/2}. \quad (5) $$

The evaporation of the PBH has a smooth behavior described by Eq. (4). However, for
simplicity, in the following discussion we will model the PBH mass to be non-evolving for temperature larger than $T_b$ and to disappear at lower temperatures. Indeed, since the evaporation rate increases rapidly near the end of the lifetime of the PBH (because of the $M^{-2}$ factor in Eq. (4)), this is a reasonable approximation for our purposes, because the timescale over which evaporation proceeds rapidly is much smaller than the lifetime of the Universe. Indeed, the same approximation is also adopted in Ref. [28] in a different model of PBH baryogenesis.

**Evolution equation of $X$.** The $X$ and $\bar{X}$ species evolve according to the interplay between different processes: the interaction with the relativistic plasma, the absorption by the cosmological distribution of PBH with number density $n_{\text{PBH}}$, and the decay via a process $X \rightarrow b + \text{SM}$, where $b$ is a SM particle with baryon number. We discuss these terms in turn.

The interaction with the plasma via the annihilation and creation processes $X\bar{X} \leftrightarrow \text{SM}$ maintains thermal equilibrium before the species becomes non-relativistic. We assume that the coupling for this interaction is the same coupling $\beta$ as for the collision cross-section, as can be expected because of crossing symmetry. After the species becomes non-relativistic, the interaction rate rapidly drops and $X$ undergoes freeze-out, as we will verify explicitly in the solutions shown below. The rate of interaction with the plasma is

$$\left( \frac{dn_X}{dt} \right)_{\text{int}} = -\langle \sigma v \rangle (n_X n_{\bar{X}} - n_{\text{th}}^2) = \frac{f^4}{m_X^2} (n_X n_{\bar{X}} - n_{\text{th}}^2),$$

where $n_{\text{th}}$ is the number density at thermal equilibrium. The absorption rate is determined by Eq. (3) and is given by

$$\left( \frac{dn_X}{dt} \right)_{\text{abs}} = -\frac{4\pi G m_X^3 \beta T_{\text{form}}}{g f^4 T} n_X n_{\bar{X}}$$

where $\beta = \rho_{\text{PBH}}(T_{\text{form}})/\rho_{\gamma}(T_{\text{form}})$ denotes the ratio between the density of PBH and the density of radiation at their formation at a temperature $T_{\text{form}} \simeq 3 \cdot 10^{15} \text{ GeV}(M_p)^{-1/2}$ [46].

The order of magnitude of the decay rate is $\Gamma = h^2 m_X n_X$, where $h$ is the coupling of the $X$ decay process. We assume here that $X$ decays into much lighter particles, so that phase space factors are negligible; furthermore, we assume that particles are at rest, since absorption becomes relevant for non-relativistic particles, and we solve the equations only in this regime. Then we have

$$\left( \frac{dn_X}{dt} \right)_{\text{dec}} = -h^2 m_X n_X.$$  

Collecting the interaction, absorption and decay terms, and observing that

$$\left( \frac{d(n_X - n_{\bar{X}})}{dt} \right)_{\text{abs}} = -\frac{4\pi G m_X^3 \beta T_{\text{form}}}{g f^4 T} \left[ f^2 \left( \frac{n_X + n_{\bar{X}}}{2} \right) + (n_X - n_{\bar{X}}) \right],$$

we obtain the evolution equations as

$$\frac{dN}{dx} = -\frac{\lambda}{x^2} (N^2 - Y_{\text{th}}^2) - \alpha x^2 N - \mu x N,$$

$$\frac{dA}{dx} = \alpha x^2 (f^2 N - A) - \mu x A,$$

where we have introduced the yields $N = \frac{n_X + n_{\bar{X}}}{2}$, $A = \frac{n_X - n_{\bar{X}}}{2}$ and $x = m/T$. Furthermore, we introduce the dimensionless parameters

$$\lambda = \frac{f^4 M_p \sqrt{g_*}}{\sqrt{45} m_X},$$

$$\alpha = \frac{\pi^4}{30 (3)} \frac{4 G \beta T_{\text{form}} \sqrt{45} M_p}{g f^4 \sqrt{4\pi g_*}},$$

$$\mu = \frac{h^2 M_p \sqrt{45}}{m_X \sqrt{4\pi g_*}},$$

and $Y_{\text{th}}$ is the equilibrium yield for the species $X$; here $M_p$ is the Planck mass and $g_* \simeq 100$ is the number of relativistic degrees of freedom appearing in the entropy density.

**Baryonic asymmetry.** Assuming that the only source of asymmetry is the decay of the $X$ particles we have

$$\frac{d\mu}{dx} = \mu x A.$$  

**Method.** The model is characterized by a number of free parameters, namely the PBH
mass $M$, the mass of $X$ $m_X$, the two couplings $f$ and $h$, and the fraction of PBHs at their formation $\beta$. We scan $10^5$ sets of such parameters and for each parameter choice we determine the numerical solution of Eqs. (10, 11, 13) assuming that $X$ is in thermal equilibrium for $x = 1$. The solutions obtained are acceptable only if a number of physical constraints are verified: $i)$ $\beta$ must be smaller than the known constraints, which are conveniently summarized in Ref. [47]. Here we neglect the constraints coming from the emission of the lightest supersymmetric particles (LSPs) composing dark matter, since these strongly depend on the mass of the LSP. Since we do not make any assumption about the nature of dark matter, these constraints can be safely evaded by assuming a lighter dark matter candidate; $ii)$ the entropy generated in the decay of the $X$ particles should not be so large as to dilute too much the generated asymmetry. Here, we conservatively require that the energy density of $X$ is always smaller than the energy density in radiation, so that the decay does not significantly enhance the entropy of the universe; $iii)$ the whole process must take place much before Big Bang Nucleosynthesis; $iv)$ we require that $X$ decays after PBHs have evaporated, so that the asymmetry in the $X$ sector has reached its largest possible value; $v)$ we require that the annihilation process $XX \rightarrow \text{SM}$ induced by the coupling $h$ is negligible compared with the annihilation induced by the coupling $f$; $vi)$ we determine the ratio between PBHs and radiation energy density at PBH evaporation (when it is at its maximum value) as $\frac{\rho_{\text{PBH}}}{\rho_{\text{rad}}} \approx \frac{\beta}{T_{\text{form}}}$, and we verify that it is smaller than 1: this guarantees that the evolution proceeds under conditions of radiation domination; $vii)$ we determine the accretion rate of mass from each PBH according to Eq. 2 at the temperature at which the PBH should evaporate, and we require that it is smaller than the evaporation rate: we quantify this requirement with the ratio

$$R_{ae} = \frac{\left(\frac{dM}{dt}\right)_{\text{acc}}}{\left(\frac{dM}{dt}\right)_{\text{eva}}},$$

where $\left(\frac{dM}{dt}\right)_{\text{acc}} = m_X \frac{dN_X}{dt}$, which we require to be smaller than 0.1. This is a fundamental requirement: were it not satisfied, PBH evaporation would be delayed by the larger accretion rate until all the species had been completely absorbed. By verifying this requirement, we ensure that the PBHs evaporate before absorbing all the $X$ particles.

As a final comment, we neglect the $X$ particles produced by PBH evaporation. This would produce a CP symmetric population of relativistic $X$ particles which therefore are much more weakly absorbed and do not lead
The production of asymmetry in this model can be understood by exhibiting a benchmark solution to the above equations for a specific parameter choice: we show this solution in Fig. 1. The yellow curve, denoting the average yield $N$ for $X$ and $\bar{X}$, undergoes freeze-out at $x$ close to 10, reaching a constant value determined by the freeze-out process. Before freeze-out, the asymmetry (blue curve) increases and reaches a plateaux value, due to the initial rapid decrease in $N$; this is a first residual component of asymmetry. After freeze-out, $N$ remains approximately constant and undergoes a slow absorption by PBHs leading to a continuous production of asymmetry, represented by the steadily increasing blue curve; this is a second component of asymmetry which starts being produced after freeze-out. We emphasize that, even though the process of freeze-out happens at $x \sim 10$, the continuous production of asymmetry dominates over the residual (plateaux) asymmetry only later, at $x \sim 10^3$. With increasing $x$, absorption becomes stronger and would eventually deplete all the species $X$ and the asymmetry produced. However, this situation is avoided because of PBH evaporation, which abruptly stops the absorption process and therefore maintains the produced asymmetry. To highlight this point, we show as a dashed line the solution determined without accounting for PBH evaporation: indeed the dashed curve vanishes for $x \sim 2 \times 10^6$. On the other hand, the solid lines remains constant immediately after PBH evaporation, when asymmetry stops being produced. At this stage, the decay into baryons allows to transfer the asymmetry from the $X$ sector into the baryonic one, represented by the green curve. The concentration of $X$ particles, and their asymmetry, completely disappear. The average energy density of $X$ and $\bar{X}$ is converted into radiation, without significantly heating the primordial plasma. A final comment is in order here: since these processes are likely to happen before the electroweak phase transition, part of the baryonic asymmetry produced in this way may be converted into leptonic asymmetry via sphaleronic processes. The final baryonic asymmetry after the sphaleron would be suppressed by a numerical factor of order 1 compared to the value predicted here. However, this only means that a slightly larger baryonic asymmetry should be produced in order to attain the present one.

We find that the correct value of the asymmetry requires a very efficient absorption, yet not so efficient that PBHs accrete all the species delaying their evaporation. In order to quantify this statement, we show in Fig. 2 the region obtained in the plane $R_{\text{ae}} - \eta_{B}^{\text{th}}$ by varying $m_X$ and $f$ and for a fixed value of $M_g$ and $\beta$ (which we choose equal to the benchmark values in Fig. 1): $R_{\text{ae}}$ is defined in Eq. 14 and $\eta_{B}^{\text{th}}$ is the final predicted asymmetry. This choice of $M_g$ and $\beta$ leads to the largest asymmetry to significant production of asymmetry. Furthermore, since they are relativistic particles, they simply remain in the plasma until the moment in which they decay. Since the total energy density of PBH remains always smaller than the radiation energy density, the decay of these relativistic particles does not lead to a substantial entropy dilution.

**Results.** The production of baryon asymmetry in this model can be understood by exhibiting a benchmark solution to the above equations for a specific parameter choice: we show this solution in Fig. 1.
value that we can produce within our model. Our results show that only a small part of the blue region lies above the experimental asymmetry (red line) and does not lead to too large an accretion (i.e., lies to the left of the gray region). Thus we find that the correct order of magnitude of the experimental asymmetry is achieved when the process is as efficient as possible given the present constraints.

Finally, we investigate the general region of the parameter space which leads to an efficient baryogenesis. In order to do so, we determine the mass of the PBH leading to the correct asymmetry for each choice of the parameters \(f\) and \(m_X\), and for three fixed benchmark values of \(\beta\). We show the contour plots of the PBH mass determined in this way in Fig. 3. The correct asymmetry is achieved for PBH masses between \(10^4\) g and \(10^7\) g, \(X\) masses between \(10^4\) GeV and \(10^{10}\) GeV, and couplings larger than about \(10^{-3}\).

This last point is especially important: indeed in Ref. [19] the need for small couplings was emphasized. However, small couplings lead to too large an absorption which suppresses the produced asymmetry before PBHs evaporate. Therefore, the opposite requirement must be met in order to produce the necessary asymmetry. Our results also show that \(\beta\) must be smaller than about \(10^{-12}\) in order to attain the solution: for \(\beta = 10^{-12}\) only a small region in the \(f - m_X\) plane leads to the correct asymmetry. This region becomes wider for \(\beta = 10^{-13}\); for smaller values of \(\beta\) the amount of PBHs is too small to produce the correct asymmetry, and already for \(\beta = 10^{-14}\) we do not find any combination of parameters for which the mechanism works.

Conclusions. In this work, we have studied a novel mechanism for baryogenesis based on an idea proposed in Refs. [18, 19]. A new species \(X\) (and its conjugate) is absorbed by primordial black holes. Since the interaction of \(X\) with the plasma surrounding PBHs is CP-violating, the \(X\) and \(\bar{X}\) absorption rates are different, yielding an asymmetry in the \(X\)-sector. In order to avoid the complete absorption of \(X\) and \(\bar{X}\), we must account for the evaporation of PBHs, which provides a natural stop to the absorption process. Once \(X\) decays into baryons, the produced asymmetry is transferred to the baryonic sector. This mechanism works through the interplay between different factors: the freeze-out of a heavy species \(X\), the CP-asymmetric absorption of this species by PBHs, and the subsequent decay of \(X\), which both transfers the asymmetry to the baryonic sector and avoids the overproduction of non-relativistic \(X\) particles which would otherwise dominate over radiation. We identify a whole region of the parameter space leading to the correct baryon asymmetry. Our work provides an effectively new baryogenesis mechanism.
mechanism which does not need violation of the baryonic number at a Lagrangian level for its success.

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