Gravitational dark matter production: primordial black holes and UV freeze-in.

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Dark matter (DM) interacting only gravitationally with the standard model could have been produced in the early universe by Hawking evaporation of primordial black holes (PBH). This mechanism is viable in a large range of DM mass, spanning up to the Planck scale. However, DM is also unavoidably produced by the irreducible UV gravitational freeze-in. We show that the latter mechanism sets strong bounds, excluding large regions of the parameter space favored by PBH production.

INTRODUCTION

Dark matter (DM) reaching chemical equilibrium with the standard model (SM) can be produced in the early universe via the WIMP paradigm [1]. Alternatively, if the interaction rates between the dark and visible sectors are not strong enough, DM can originate non-thermally through the FIMP mechanism [2–6].

However, it is also conceivable that DM only interacts gravitationally with the SM. In this scenario, DM can be radiated by primordial black holes (PBH) [7–19] during their Hawking evaporation [20]. This mechanism is viable in a large range of DM mass, spanning up to the Planck scale. PBHs evaporating before BBN are poorly constrained [21, 22] and therefore potentially produce the whole observed DM abundance.

Another purely gravitational DM production mechanism corresponds to the UV freeze-in due to annihilation of SM particles via the s-channel exchange of gravitons [23–26]. The massless SM gravitons mediate between the dark and the visible sectors, producing DM during the heating epoch. Being a gravitational process, its contribution is Planck suppressed and can be dominant for high reheating temperatures \( T_{\text{rh}} \). Additionally, it only depends on \( T_{\text{rh}} \), the DM mass \( m_{\text{DM}} \) and its spin.

In this Letter, the interplay of these two gravitational DM production mechanisms is studied. In particular, we show that the parameter space favored by the DM production via Hawking radiation is severely constrained when taking into account the irreducible gravitational UV freeze-in.

DARK MATTER FROM PRIMORDIAL BLACK HOLES

PBHs formed in a radiation-dominated epoch, when the SM plasma has a temperature \( T_{\text{in}} \), have an initial mass \( M_{\text{in}} \) given by [16, 21, 22]

\[
M_{\text{in}} = \frac{4\pi}{3} \gamma \frac{\rho_R(T_{\text{in}})}{H^2(T_{\text{in}})},
\]

where \( \gamma \approx 0.2 \), \( \rho_R \) and \( H \) are the SM energy density and the Hubble expansion rate, respectively.

PBH evaporation produces all particles, and in particular extra radiation that can modify successful BBN predictions. To avoid it, we require PBHs to fully evaporate before BBN time, i.e. \( T_{\text{BBN}} \approx 4 \text{ MeV} \) [27–31]. This, together with the upper bound on the inflationary scale reported by the Planck collaboration \( H_I \lesssim 2.5 \times 10^{-5} M_P \) [32], bounds the initial PBH mass

\[
0.1 \text{ g} \lesssim M_{\text{in}} \lesssim 2 \times 10^8 \text{ g}.
\]

An additional upper bound on \( M_{\text{in}} \) appears if one requires the PBHs to generate the whole observed DM relic abundance. In the case where PBHs dominate the universe energy density before their decay [19]

\[
M_{\text{in}} \lesssim \begin{cases} \frac{C^2 M_P m_{\text{DM}}^5}{(m_{\text{DM}} Y_{\text{DM}})^2} & \text{ for } m_{\text{DM}} \leq T_{\text{in}}^\text{BH}, \\ \left[\frac{C^2 M_P^2}{m_{\text{DM}} Y_{\text{DM}}^2}\right]^{1/5} & \text{ for } m_{\text{DM}} \geq T_{\text{in}}^\text{BH}, \end{cases}
\]

where \( T_{\text{in}}^\text{BH} \equiv M_P^2/M_{\text{in}} \) is the initial PBH temperature, \( C \equiv 2\sqrt{5}\pi^3/16 \), \( \zeta_3 \), \( g_s \) the number of relativistic degrees of freedom contributing to the SM radiation energy density, \( g_T \) the number of DM degrees of freedom, and \( C_n = 1 \) or \( 3/4 \) for bosonic or fermionic DM, respectively. Additionally, \( Y_{\text{DM}} \) is the DM yield at present satisfying \( m_{\text{DM}} Y_{\text{DM}} \approx 4.3 \times 10^{-10} \text{ GeV} \) to match the observed DM relic abundance \( \Omega_{\text{DM}} h^2 \approx 0.12 \) [33].

Values of \( M_{\text{in}} \) violating the bound on Eq. [3] produce a DM underabundance.

Moreover, PBHs radiate ultra-relativistic DM [10, 13, 19, 34] that could have a large free-streaming length that suppresses structure formation at small scales. Taking...
in its mean velocity to be \( v_{DM} \lesssim 1.8 \times 10^{-8} \) \( \text{for } m_{DM} \simeq 3.5 \text{ keV} \) [35]:

\[
\frac{m_{DM}}{\text{1 GeV}} \gtrsim 2 \times 10^{-3} \left( \frac{M_{\text{in}}}{g} \right)^{1/2}.
\] (4)

The color shaded areas in Fig. 1 summarize the previously described constraints on the parameter space \([m_{DM}, T_{in}]\), for scalar DM with \( g_{DM} = 1 \). Red corresponds to the CMB and BBN bounds in Eq. (2), green to the underabundance region in Eq. (4) and blue to hot DM in Eq. (4). In the white regions, the observed DM relic abundance can be obtained by PBH evaporation, for a given initial PBH energy density.

**GRAVITATIONAL UV FREEZE-IN**

Independently from the PBH evaporation, there is an irreducible DM production channel which is particularly efficient in the region favored by Fig. 1 and corresponds to the gravitational UV freeze-in. DM can be generated via 2-to-2 annihilations of SM particles, mediated by the exchange of massless gravitons in the s-channel. Its contribution to the total DM density is [26]

\[
\frac{\Omega_{DM} h^2}{0.12} \lesssim 4.2 \times 10^{-13} \alpha_{DM} \frac{m_{DM}}{\text{1 GeV}} \left( \frac{T_{rh}}{10^{12} \text{ GeV}} \right)^3.
\] (5)

where \( \alpha_{DM} = 1.9 \times 10^{-4}, 1.1 \times 10^{-3} \) or \( 2.3 \times 10^{-3} \) for scalar, fermionic, or vector DM, respectively. The equality corresponds to the case where the whole DM abundance is produced via the graviton exchange. We notice that the DM production has a strong dependence on the reheating temperature, characteristic of the UV freeze-in mechanism. We note that the temperatures \( T_{rh} \) and \( T_{in} \) are in principle unrelated, however, \( T_{rh} \geq T_{in} \) to guarantee that PBHs are produced after the onset of the radiation domination era. Additionally, 2-to-2 scatterings require \( T_{rh} \geq m_{DM} \) to be kinematically allowed.

In order not to overclose the universe, the loosest upper bound on the DM mass from Eq. (5) corresponds to \( T_{in} \simeq T_{rh} \), whereas the tightest one appears when \( T_{rh} \) takes its highest allowed value \( T_{rh} \simeq 10^{16} \text{ GeV} \) [32]. Nevertheless, it is important to note that the DM yield in Eq. (5) can be significantly boosted when considering a non-instantaneous decay of the inflaton [36, 37], and in particular due to nonthermal effects [38], or expansion eras dominated by a fluid component stiffer than radiation [39, 40].

In Fig. 1 the constraint due to DM overabundance produced by UV freeze-in is overlaid in gray. The upper panel corresponds to \( T_{rh} = T_{in} \) or \( T_{rh} = 10^{16} \text{ GeV} \), and the lower panel to \( T_{rh} = 10^{14} \text{ GeV} \), within the instantaneous decay approximation for the inflaton. The regions where \( T_{in} > T_{rh} \) are also shown. We notice that the gravitational UV freeze-in sets strong constraints, excluding large regions of the parameter space favored by PBHs production of DM.

**CONCLUSIONS**

The observed abundance of dark matter (DM) particles that only interact gravitationally with the standard model (SM) could have been produced in the early universe by Hawking evaporation of primordial black holes (PBH). This mechanism is viable in a large range of DM masses, spanning up to the Planck scale, and for PBHs produced shortly after the reheating epoch. However, in this same range of parameters, the irreducible UV gravitational freeze-in production, where DM particles are
produced from the SM via the exchange of gravitons, is active and efficient. We showed that the latter mechanism sets strong bounds, excluding large regions of the parameter space favored by PBH production. We note that these bounds on super heavy DM could be even stronger if DM couples to the inflaton. In that case, DM can be efficiently produced by the decay of the inflatons from the heating era, or generated from PBH evaporation.

Before concluding, we note that if DM features sizable self-interactions, number-changing processes can enhance the PBH DM production while decreasing the mean DM kinetic energy \[h^2 < 0.12\] bounds on the left of Fig. [1] can be significantly eased.

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