Erratum: Dark Matter from Exponential Growth [Phys. Rev. Lett. 127, 191802 (2021)]

Torsten Bringmann[✉], Paul Frederik Depta, Marco Hufnagel, Joshua T. Ruderman, and Kai Schmidt-Hoberg

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In our Letter, we provide an example realization of dark matter (DM) production via exponential growth, where the heat bath particle ψ is coupled to the standard model (SM) via the Higgs portal, $\lambda_{h\psi}|H|^2\psi^2/2$. The DM particle χ is initially produced by freeze-in via $\psi\psi \rightarrow \chi\chi$, induced by the term $\lambda_{\text{fi}}\psi^2\chi^2/4$, until the transformation process $\chi\psi \rightarrow \chi\chi$, as induced by a term $\lambda_{\text{tr}}\psi\chi^3/6$, takes over and leads to exponential growth. By connecting one outgoing ψ of the Higgs-portal vertex to a transformation vertex, cf. Fig. 6, one, however, also obtains a freeze-in contribution via $\text{SM SM} \rightarrow \psi\chi\chi\chi$ that we missed in our analysis. By calculating the exact cross-section for this process using Feynrules [1] and MADGRAPH5 [2], we find that this additional process produces more DM than $\psi\psi \rightarrow \chi\chi$ if $\lambda_{\text{fi}} \lesssim \lambda_{h\psi}\lambda_{\text{tr}}/[3(4\pi)^2]$, where we explicitly find an enhancement of ~ 3 compared to the factor $(4\pi)^2$ naively resulting from phase-space suppression. This condition is satisfied within the entire parameter region shown in Fig. 5 of this Letter, implying that we underestimated the initial abundance before the onset of exponential growth, leading to an overproduction of DM in the entire parameter region. In particular, the possibility of exponential DM production for large $m_\psi > 1$ TeV in the Higgs-portal example is excluded.

To allow for exponential growth in the Higgs-portal example, we thus need a smaller coupling $\lambda_{h\psi}$, without ψ becoming the dominant DM component. In order not to violate limits from invisible Higgs decays [3] or direct detection with Xenon1T [4], this only leaves the region of resonant ψ annihilations, $m_\psi \sim m_h/2$ [5]. We show an explicit example for $m_\psi = m_h/2$ in Fig. 7. The relic density of ψ is set by freeze-out, where we took into account the effect of early kinetic decoupling as implemented in DarkSUSY [6] and we adjust the coupling to $\lambda_{h\psi} = 3.9 \times 10^{-4}$ such that ψ accounts for 20% of DM. We then adjust λ_{fi} for every m_χ and λ_{tr} to produce 80% of the total DM abundance in χ . The dominant production mechanisms are indicated by green and blue regions for freeze-in and exponential growth, respectively. In the light blue region, 2-to-4 freeze-in via the Higgs portal, neglected in our original calculation, dominates freeze-in production over $\psi\psi \rightarrow \chi\chi$, generally leading to DM overproduction as discussed above.

Because of the decreased value of $\lambda_{h\psi}$, the cosmic-microwave-background (CMB) signatures from ψ decay disappear for $m_\chi < m_\psi$. Hence, we focus on the region $m_\chi > m_\psi$, where χ decays into ψ and SM final states, predominantly by two-loop diagrams involving one freeze-in and one transmission vertex as well as the Higgs portal to a (potentially off-shell) Higgs boson decaying into SM final states. (Possible three-loop diagrams with three transmission vertices are suppressed as λ_{tr} cannot get large enough without reaching the light blue region.) We roughly estimate a decay width of

$$\Gamma_\chi \simeq \frac{\lambda_{h\psi}^2 v^2}{16\pi m_\chi^3 (4\pi)^8} \int_0^{(m_\chi - m_\psi)^2} \frac{dq^2}{2\pi} 2q \Gamma_h(q) \times \frac{\sqrt{[m_\chi^2 - (m_\psi + q)^2][m_\chi^2 - (m_\psi - q)^2]}}{(q^2 - m_h^2)^2 + m_h^2 \Gamma_h^2(m_h)}, \quad (1)$$

FIG. 6. Feynman diagram for 2-to-4 freeze-in via the Higgs portal.

FIG. 7. Phenomenological consequences of a specific example realization of exponential production, where ψ is coupled to the SM via the Higgs portal in the regime of resonant annihilations ($m_\psi = m_h/2$). We fix $\lambda_{h\psi} = 3.9 \times 10^{-4}$, giving 20% of DM in ψ , and choose $\lambda_{\tilde{h}}$ for each m_χ and λ_{tr} such that χ provides 80% of the observed DM abundance. Green and blue regions indicate which production mechanism dominates the χ abundance. Red lines (and the hatched area) show where CMB signatures can naturally be expected. Within the light blue region, freeze-in via $hh \rightarrow \psi\chi\chi\chi$ dominates the initial χ abundance over $\chi\chi \rightarrow \psi\psi$, thus generically leading to overproduction of DM.

where $v \approx 246$ GeV is the Higgs vacuum expectation value, and $\Gamma_h(q)$ is the off-shell decay width of a Higgs boson with invariant mass q (which we evaluate using HDECAY [7]). This decay can alter the CMB power spectrum, constrained to a lifetime $\tau_\chi = 1/\Gamma_\chi \gtrsim 0.8 \times 10^{24}$ s for 80% of DM in χ [8]. CMB-S4 is expected to strengthen this constraint by a factor of ~ 3 [9]. We show where the naïve expectation of the lifetime is in conflict with these constraints or may be tested by CMB-S4 with the hatched area and red lines in Fig. 7. For $m_\chi < m_\psi + m_h = (3/2)m_h$, the Higgs can only be produced off shell, resulting in a significant suppression of the decay width and hence the absence of CMB limits in this parameter range.

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