FROM EXTENDED THEORIES OF GRAVITY TO DARK MATTER*

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In this work, we propose different models of extended theories of gravity, which are minimally coupled to the SM fields, to explain the possibility of a dark matter (DM) candidate, without *ad hoc* additions to the Standard Model (SM). We modify the gravity sector by allowing quantum corrections motivated from local $f(R)$ gravity, and non-minimally coupled gravity with SM sector and dilaton field. Using an effective field theory (EFT) framework, we constrain the scale of the EFT and DM mass. We consider two cases — Light DM (LDM) and Heavy DM (HDM), and deduce upper bounds on the DM annihilation cross section to SM particles.

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Majority of the matter in this universe occurs in the form of dark matter (DM). A general approach to explain the existence of a DM candidate is an *ad hoc* addition of a new particle, intended to serve as the DM. However, that is not always theoretically well-motivated. To explain the genesis of a DM candidate, we propose an alternate framework based on the principles of EFT.

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Here, we start with the extended version of gravity sector keeping the SM matter sector unchanged. The cases considered are given by:

$$S = \begin{cases} \int \mathrm{d}^4x\sqrt{-g}\left[\frac{\Lambda_{\mathrm{UV}}^2}{2}\left(aR+bR^n\right)+\mathcal{L}_{\mathrm{SM}}\right], & f(R) \text{ gravity}, \\ \int \mathrm{d}^4x\sqrt{-g}\left[\frac{\Lambda_{\mathrm{UV}}^2}{2}\left(1+\xi\frac{\phi^2}{\Lambda_{\mathrm{UV}}^2}\right)R+\mathcal{L}[\phi]+\mathcal{L}_{\mathrm{SM}}\right], & \text{non-minimal gravity}, \end{cases}$$

where Λ_{UV} is the scale of new physics. For these classes of gravity theory, after conformally transforming the metric in the *Jordan frame* into *Einstein frame*, we get

$$S \Longrightarrow \tilde{S} = \int \mathrm{d}^4x\sqrt{-\tilde{g}}\left[\frac{\Lambda_{\mathrm{UV}}^2}{2}\tilde{R} - \frac{1}{2}\tilde{g}^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi) + e^{-\frac{2\sqrt{2}}{\sqrt{3}}\frac{\phi}{\Lambda_{\mathrm{UV}}}}\mathcal{L}_{\mathrm{SM}}\right], \tag{1}$$

where the new scalar field, "dilaton" (ϕ), generated through conformal transformations, is identified as the DM candidate. The potential term $V(\phi)$ has terms which involve self interaction of DM and can be used to constrain the parameters of these extended theories, as shown in [1]. Assuming that the scale of new physics is large, we expand the Lagrangian as

$$e^{-\frac{\phi}{\Lambda_{\mathrm{UV}}}}\mathcal{L}_{\mathrm{SM}} \xrightarrow{\mathcal{Z}_2} \left\{1 + \frac{\phi^2}{2\Lambda_{\mathrm{UV}}^2}\right\}\mathcal{L}_{\mathrm{SM}}\,. \tag{2}$$

Thus, here, DM couples *universally* to SM at the higher orders. We consider the cases of LDM (10 GeV $< M <$ 350 GeV) and HDM (350 GeV $< M <$ 1 TeV). The scale associated with HDM is larger than that of LDM and this distinguishes the two cases. The annihilation channels considered for calculation of the relic density are shown in Fig. 1. We calculate the relic density using (up to p-wave expansion) [2]

$$[\sigma v]_{NR} = a(\Lambda_{\mathrm{UV}}, M) + b(\Lambda_{\mathrm{UV}}, M)v^2 + \ldots$$

Using the experimental bounds on relic density observed by Planck 2015 [3], we deduce constraints on the DM mass and scale of new physics $(M, \Lambda_{\mathrm{UV}})$.

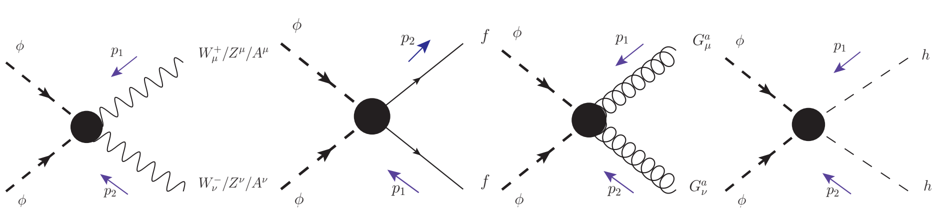

Fig. 1. Effective processes contributing to relic density of DM. Here, $2 \to 3$ and $2 \to 4$ processes are suppressed.

We present plots of the allowed parameter space in Fig. 2. We have allowed the fact that the dilaton may not be the only DM candidate, in which case it can contribute to a certain fraction of the relic. We show cases where the dilaton contributes to 10% and 50% of the 2σ relic bounds. In Fig. 3, we show the annihilation cross section of DM to $b\bar{b}$ and $\tau\bar{\tau}$, assuming these to be the main annihilation channels. We see similar features for both LDM and HDM candidates. However, for HDM, the cross sections are well below the current experimental sensitivity and cannot be probed by present experiments. The cases for other channels are presented in [1].

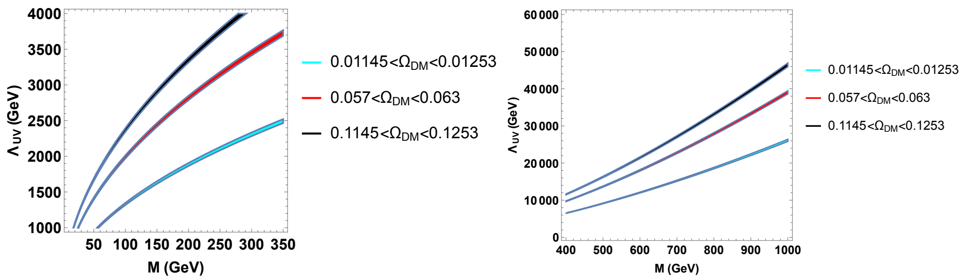

Fig. 2. (Colour on-line) Allowed parameter space for LDM (left) and HDM (right) candidate. Black denotes 2σ bounds, while grey/red and light grey/cyan denote 50% and 10% of the 2σ relic bounds.

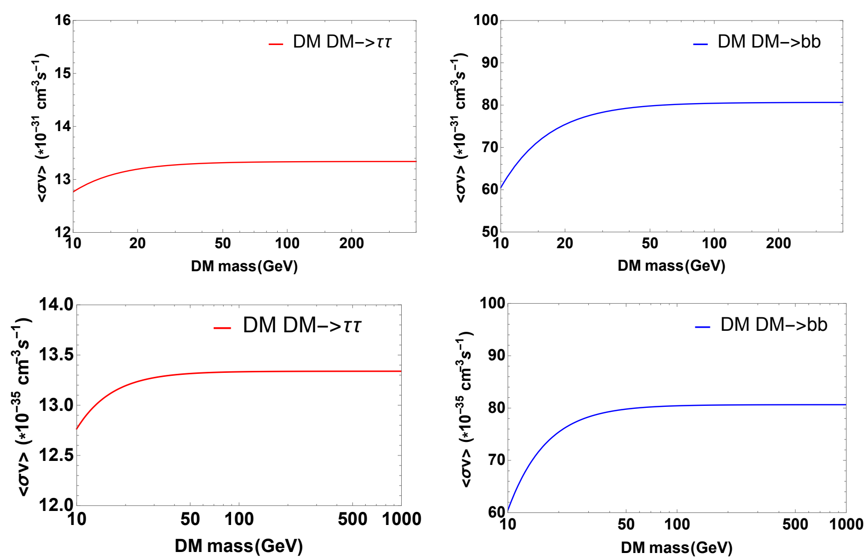

Fig. 3. Annihilation cross sections of DM to $b\bar{b}$ and $\tau\bar{\tau}$ for LDM (top panel) and HDM (bottom panel) candidate. The values obtained are well within the bounds given in [4].

In conclusion, we have presented a DM candidate which is generated solely from the gravity sector. Based on whether our candidate is LDM or HDM, we have presented the corresponding allowed parameter space and bounds.

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